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PHOSPHATE REMOVAL IN AN ACTIVATED
SLUDGE FACILITY

Richard E. Finger, et al

Seattle Metropolitan Municipality

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For

Advanced Waste Treatment Research Laboratory
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NATIONAL ENVIRONMENTAL RESEARCH CENTER
OFFICE OF RESEARCH AND DEVELOPMENT
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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

This report illustrates the combination of biological and engineering controls that are necessary to accomplish efficient phosphorus removal from a municipal wastewater effluent.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center, Cincinnati

ABSTRACT

Biological and chemical means of phosphorus removal were studied at the Municipality of Metropolitan Seattle's activated sludge facility in Renton, Washington. The studies ranged from jar tests to full scale plant manipulation. Only the secondary activated sludge system was studied.

The results of these studies indicate that the observed removal of phosphorus, in a soft water area activated sludge facility, is primarily biological in nature. Some increase in removal can be encouraged by judicious control of organic loading rates, air application rates and excess sludge wasting rates. However, even under optimum conditions, this biological mechanism fails to consistently reduce the phosphorus concentration to the desired level of less than 1.0 mg/l.

Both ferric chloride and alum were found to be effective in removing phosphorus when added to the activated sludge culture. Both can be controlled by automatic means to give the desired concentration of phosphorus in an activated sludge effluent. Addition of either chemical produces more sludge mass. The density of the sludge produced with alum will be greater, thus producing less volume to handle. Alum is more effective than ferric chloride in causing an increased density of the final sludge.

Initial capital costs for either chemical are the same except for the requirement of a larger volume storage tank for the alum. Chemical costs will vary depending on location of the supplier in relation to the plant. Alum costs at the Renton plant are \$16.80 per million gallons and ferric chloride costs are \$34.20 per million gallons not including delivery. These figures represent a cost of \$2.88 and \$5.50 per mg/l phosphorus removed per million gallons for alum and ferric chloride, respectively.

This report was submitted in fulfillment of Project Number WPRD 247-01 and Demonstration Grant Number 17010 EDA by the Municipality of Metropolitan Seattle under the partial sponsorship of the Environmental Protection Agency. Work was completed as of June 30, 1972.

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To the many graduate students and other personnel of the University of Washington who produced more than was ever expected, we wish to express our sincere thanks.

SECTION I

CONCLUSIONS

1. Up to 50% phosphorus removal can be achieved by the biological process at the Renton treatment plant which does not recycle anaerobic digester supernate to the plant influent.
2. Operating conditions that promote rapid biological growth can increase the rate of phosphorus uptake significantly.
3. While bench scale and jar tests were not adequate tools in this study for predicting full scale behavior, particularly relating to biological phosphorus removal, they can be useful tools for predicting chemical effects on a full scale facility.
4. Ferric chloride and aluminum sulfate react instantaneously with phosphorus in soft water areas. Both chemicals reduce the pH of the mixed liquor which could be a problem depending on the alkalinity and phosphorus content of the water being treated.
5. Sodium aluminate causes an increase in pH in soft water areas thus inhibiting the phosphorus complexing reaction.
6. Precipitation of phosphorus with aluminum is pH dependent. The ratio of aluminum to phosphorus required to achieve a fixed removal of phosphorus is at a minimum at pH 6.0 and increases as the pH rises to 8.0. A similar situation exists with iron at different pH's.
7. Alum effectively removes phosphorus when added to an activated sludge system and causes a definite increase in the density of the activated sludge. Alum is easy to handle and presents a minimum of problems with respect to corrosion and safety.
8. Ferric chloride is effective in phosphorus removal but does not cause a significant reduction in the sludge density. Ferric chloride is difficult to handle due to its extreme corrosiveness.
9. In the case of both ferric chloride and alum, the estimated quantity of chemical required on the basis of jar tests was significantly greater than was actually required. This resulted from a failure to account for the reduction in mixed liquor phosphorus levels resulting from

the recycle of return sludge having a very low soluble phosphorus concentration.

10. There was no change in the required chemical to phosphorus ratios as the test proceeded. The recycle of return sludge having a significant level of metal salts, therefore, did not contribute to an enhanced phosphorus removal.

11. Alum costs were \$16.80 per million gallons treated, while ferric chloride costs were \$34.20 per million gallons treated at the Renton plant, not including shipping costs. These represent costs of \$2.88 and \$5.50/mg/l phosphorus removed/MG for alum and ferric chloride, respectively.

12. Capital costs for a complete storage and control system for either chemical are approximately \$26,000 for a 24 MGD facility. The major portion of the costs is attributable to analyzer and control equipment. This cost is largely independent of the plant size.

13. Alum was the best chemical for removal of phosphorus at the Renton plant on the basis of cost, ease of handling and effect on settling. Costs are directly related to removal efficiencies with alum costs being approximately half the ferric chloride costs to achieve equivalent phosphorus removals.

SECTION II

RECOMMENDATIONS

1. Further research into the nature and control of biological phosphorus uptake in full scale activated sludge facilities should be done. The answers obtained would add to our basic fund of knowledge and aid in the development and selection of the most economical phosphorus removal procedure.
2. Adequate mixing facilities for chemical addition should be provided to insure efficient utilization of the added chemical. Normal aeration basin mixing is not sufficient to prevent excessive loss of the metal as the metal hydroxide through hydrolysis reactions.
3. Activated sludge systems using chemical addition for phosphorus removal and having an alkalinity less than 150 ppm and a phosphorus concentration greater than 10 ppm should have facilities for pH control. Otherwise, loss of the biological culture can be expected.
4. A second phosphorus analyzer equipped with a high level alarm should be provided at the outlet of the clarifiers to provide backup control of the chemical addition.
5. A magnetic flow meter or variable speed proportioning pump should be used to provide accurate measurement and control of the chemical feed.
6. Total flow and phosphorus concentration at the chemical addition point must be known to insure that the optimum chemical to phosphorus ratio is maintained. Addition of chemicals to the aeration basin will require that the plant flow and the return sludge flow be summed to obtain the correct flow for use on the chemical feed control loop.
7. The chemical feed controller phosphate analyzer should be equipped with high and low level alarms to protect against autoanalyzer malfunction.
8. It is important to select a chemical feed point or points which require a minimum number of controllers while pro-

viding sufficient low energy mixing following the chemical addition to allow for flocculation.

9. The use of polyelectrolytes in conjunction with alum or ferric chloride feed should be investigated. Such a procedure could effectively reduce the effluent phosphorus level by trapping colloidal floc which would otherwise be discharged with effluent.

SECTION III

INTRODUCTION

During the last ten years there has been a new awareness of environmental problems and a growing concern about man's effects on his surroundings. The effects of discharging wastewater treatment plant effluents into our streams and lakes has been one of the prime concerns. The quantities of phosphorus in these effluents has led to major industrial research in an attempt to substitute other materials for phosphorus in detergents. Many research projects have been conducted at universities and municipalities to discover an economical method for removing phosphorus in wastewater treatment plants. Most of the studies have described methods of operation that are applicable to only one particular plant with inadequate information about the nature of the reaction to make the proposed method transferable to other treatment plants. The removal of phosphorus at the Rilling Plant in Amarillo, Texas (1) and at the Hiperion Plant(2) can be explained chemically. Both of these studies were conducted in areas having water with a very high calcium and magnesium content.

Since the Municipality of Metropolitan Seattle's (Metro) Renton Treatment Plant is located in a soft water area, it was felt that a demonstration of an efficient, economical method for removing phosphorus at this location could provide useful information for helping other plants in soft water areas meet the increasingly stringent standards for phosphorus removal.

SCOPE OF THE PROJECT

Phosphorus removal at Renton was investigated in the activated sludge process with no work performed in the primary treatment area. Both biological removal and removal through the addition of chemicals to the activated sludge culture were studied.

The biological studies included laboratory experiments prior to full scale application. Computerized statistical techniques were applied to the data generated from both the laboratory and full scale experiments. Both controlled experimental techniques and long term studies were conducted and analyzed during the full scale operation.

Chemical studies were conducted in the laboratory using jar scale and bench scale tests. Further pilot plant studies were conducted to obtain information on the long term effect of chemical addition. A control system for chemical dosing in proportion to the quantity of phosphorus present was developed for the full scale test during which ferric chloride and aluminum sulfate were used. This report will be restricted to the discussion of the full scale studies. Data on the jar, bench and pilot studies is available on a loan basis from the Municipality of Metropolitan Seattle.

PLANT DESCRIPTION

The Metro Renton Treatment Plant is an activated sludge plant with aerated grit removal, primary settling and an average summer daily flow of 22 MGD. The design flow during this study was 24 MGD and has since been expanded to 36 MGD. The ultimate design capacity is 144 MGD. The plant is located in a softwater area and receives predominantly domestic sewage. The only major industrial complex discharging to the plant is a dairy product facility which provides approximately one third of the total plant BOD loading.

The Renton Treatment Plant is designed to provide a high degree of flexibility in the aeration system. Aerator feed can be varied from plug through step to contact stabilization while aeration can be varied from conventional to tapered with a minimum of difficulty. Each aeration tank has a total of twelve dissolved oxygen probes and is divided into two, two-pass systems with respect to aeration control. With this arrangement, any one of the first six probes can be used for dissolved oxygen control in the first two passes, and any one of the second six probes can be used for control in the second two passes. The aeration rate can also be controlled manually. The dissolved oxygen probes provide a continuous dissolved oxygen profile throughout the tank. The total volume of each of the two four-pass aeration tanks is four million gallons.

Mixed liquor is carried from the aeration tanks to the final clarifiers through an aerated mixed liquor channel having a volume of 0.58 million gallons. The return activated sludge from the clarifiers can be varied from 6 MGD to 60 MGD and can be controlled either manually or automatically as a percent of the influent flow.

Effluent from the secondary clarifiers is collected and chlorinated after which it is discharged to a chlorine contact channel which provides 46 minutes detention time at the design flow. The chlorine feed rate is controlled by a continuous chlorine analyzer and the total chlorine residual is normally held at 1.5 mg/l at the control point. The effluent from the chlorine contact channel is discharged to the Green River.

Excess activated sludge can be wasted from the system as either mixed liquor or return activated sludge. The waste activated sludge is combined with the primary raw sludge and scum and the combined waste sludges are pumped to the Metro west side collection system. These combined wastes then flow to the West Point plant where they are resettled and anaerobically digested. This procedure eliminates the necessity of maintaining digesters at the Renton plant and thus eliminates the discharge of phosphorus rich digester supernate to the plant influent.

The design data sheet for the plant at the time of the study is presented in Table 1. A diagram of the Renton Treatment Plant during the period of the study is presented in Figure 1.

Table 1 • Design Data for the Renton Plant

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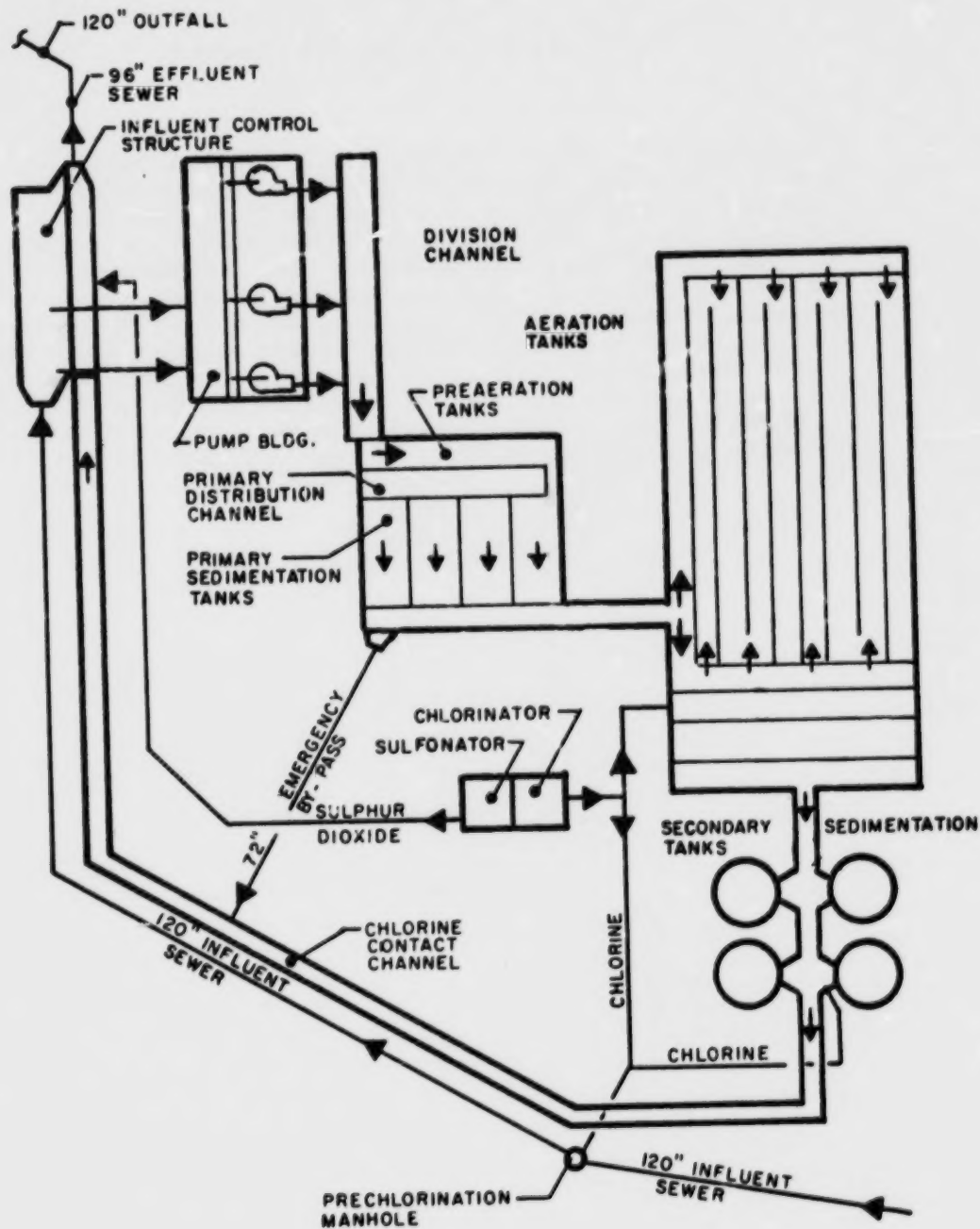


FIGURE 1
RENTON TREATMENT PLANT EXISTING FACILITIES

SECTION IV
PLANT MODIFICATIONS FOR PROJECT

The chlorine contact channel at the Renton plant has a design detention time of 45.9 minutes. The addition of chlorine at the head of the channel promotes flocculation and settling of any solids that may pass through the secondary clarification process. Low velocities in this channel allows most of these solids to settle in the channel and, unless they are removed, anaerobic decomposition will occur with release of previously entrapped phosphorus to the effluent. A flushing gate was installed near the discharge end of the channel to allow frequent flushing of these solids to the influent sewer. This flushing prevents phosphorus release to the effluent.

SECTION V

GENERAL PLAN

The project plan called for the optimization of biological phosphorus removal followed by the use of chemical addition to the secondary treatment process to increase phosphorus removal to the desired level. A final effluent phosphorus concentration of 1.0 mg/l or less was the desired goal.

Jar and bench scale tests were conducted for both the biological and chemical removal studies and the results of these tests were applied to the full-scale tests. The results of these jar and bench scale tests will not be discussed except as they applied to the full-scale testing activities. These data are available from Metro on a loan basis. Table 2 shows the sequence of activity for the full-scale plant tests.

BIOLOGICAL FULL SCALE STUDY

After obtaining background data on normal plant operating parameters, the plant was operated in such a fashion that the results of the jar tests and anomalies in the background data could be studied. In all cases an attempt was made to integrate a controlled experimental approach with real operating conditions. Particular attention was given to operator-controlled variables. The controllable variables examined were return activated sludge rate, mixed liquor solids concentration, waste activated sludge rate, aeration rate and dissolved oxygen concentration. The system was allowed to stabilize at a given set of operating conditions for at least a week before intensive sample collection and analysis was undertaken. The non-controllable parameters which were monitored were effluent biochemical oxygen demand BOD, primary effluent phosphorus concentration, return activated sludge phosphorus concentration, effluent collection chamber phosphorus concentration, final effluent BOD, final effluent phosphorus residual, settling, primary effluent calcium concentration, primary effluent magnesium concentration, and total plant flow. In each case the data generated was computerized and statistical techniques were used to determine any significant relationships to phosphorus removal.

Table 2. ACTIVITY SCHEDULE

DATE	ACTIVITY	AGENCY
October 1969	Plant detention time studies begun	Municipality of Metropolitan Seattle
November 1969	Plant switched from 2-pass to 4-pass aeration due to high flows	Municipality of Metropolitan Seattle
February 1970	Plant detention time study completed	Municipality of Metropolitan Seattle
April 1970	Background biological data collection	Municipality of Metropolitan Seattle
May 1970	Plant background data collection completed	Municipality of Metropolitan Seattle
June 1970	Plant scale biological removal tests begun	Municipality of Metropolitan Seattle
August 1970	Attempted full-scale duplication of Hyperion work(2)	Municipality of Metropolitan Seattle
January 1971	Preparation for full scale chemical tests	Municipality of Metropolitan Seattle
April 1971	Construction of chemical feed system	Municipality of Metropolitan Seattle
April 1971	Full scale biological tests completed	Municipality of Metropolitan Seattle
June 1971	Full scale alum feed test completed	Municipality of Metropolitan Seattle
August 1971	Full scale ferric chloride feed test completed	Municipality of Metropolitan Seattle
August 1971	Statistical analyses of biological removal completed	Municipality of Metropolitan Seattle
March 1972	Analysis of full scale chemical data completed	R. W. Beck
April 1972	Final report written	Municipality of Metropolitan Seattle Municipality of Metropolitan Seattle University of Washington

FULL SCALE CHEMICAL STUDIES

Aluminum sulfate and ferric chloride were selected for application during the full scale plant study. The chemical addition was controlled in direct proportion to the mixed liquor supernate phosphorus concentration and the wastewater flow. Intensive sampling and analysis was conducted during these test periods to ascertain the effectiveness of the chemical on phosphorus removal and the effect of the chemical on the biota of the activated sludge culture.

SECTION VI

MATERIALS AND METHODS

Detention Time Studies

Dye studies, using Rhodamine WT dye because of its low adsorbitivity on the activated sludge, were conducted to accurately determine the detention times between various points in the plant. The plant flow was held constant during the tests and the fluorescence of the supernate from centrifuged samples was measured with a Turner fluorometer. A plot of fluorescence versus time from addition was prepared such as is shown in Figure 2 and the time of peak fluorescence was designated as the detention time for the given flow.

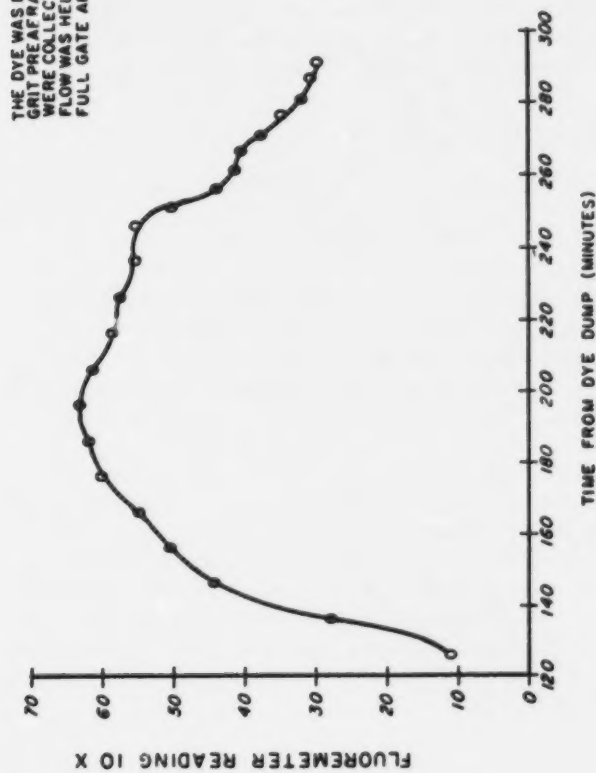
The results of these studies were used to trace a plug of sewage through the plant to allow proper correlation of the full-scale biological data. A multiple iteration calculation was performed with a computer to order the experimental data with respect to flow through the plant.

Analytical Procedures

Sample analyses during the project involved the determination of a number of different parameters. Alkalinity, biochemical oxygen demand and chemical oxygen demand analyses were run according to the 12th edition of Standard Methods (3). The chemical oxygen demand was run with a fifteen minute reflux as this method gave a complete reaction with the Renton sewage.

Total and volatile suspended solids were run by a modification of the procedure found in the 12th edition of Standard Methods (3). The modification involved the use of a glass fiber filter pad in place of the asbestos mat. All other conditions were as specified in Standard Methods (3).

Calcium and magnesium data for the routine daily analyses were analyzed according to the 12th edition of Standard Methods (3) by the ethylenediaminetetracetic acid titration using Eriochrome Black T and Murexide as indicator for total hardness and calcium hardness, respectively. Potassium cyanide was used as an inhibitor for the total hardness test. Calcium and magnesium data for the full scale plant tests were obtained by means of an atomic absorption spectrophotometer as were all iron data.



THE DYE WAS DUMPED AT THE END OF THE GRIT PREAFRATION CHANNEL AND SAMPLE WERE COLLECTED BY INLET GATE NO. 38. FLOW WAS HELD AT 15 MGD. GATE 31 HAD A FULL GATE AND GATES 5 AND 6 HAD GATES.

FIGURE 2
DYE STUDY PLOT

Sulfate analyses were run by the turbidimetric procedure while chloride was analyzed by the mercuric nitrate titration procedure, both of which are presented in Standard Methods (3). The aluminum analyses were performed by the Eriochrome Cynaine R procedure (4).

Ortho-phosphate data was determined by the single reagent method as presented in the 1970 edition of "Methods for Chemical Analysis of Water and Wastes" published by the EPA. Total (organic & inorganic) phosphorus data were analyzed with a Technicon Autoanalyzer by a high temperature digestion method. The flow diagrams and reagent compositions for this analysis are contained in Figures 3 and 4. A new autoanalyzer system was obtained during the later part of the study and all total phosphorus data from the plant scale tests were obtained using the new system. The flow diagrams and reagent compositions for this system are presented in Figures 5 and 6 and Table 3.

Chemical Feed Controller

As the first step in the preparation for the full-scale chemical feed tests, it was necessary to design and construct a chemical feed control system capable of delivering the various test chemicals at a rate proportional to the quantity of phosphorus present at the addition point. In order to accomplish this, it was necessary to measure the flow and the phosphorus concentration at the feed point. The product of these two parameters was used to generate the control signal.

The ortho-phosphate concentrations in the mixed liquor supernate was measured with a Technicon autoanalyzer system equipped with a continuous filter for removal of the mixed liquor suspended solids. Since the electrical signal generated by the autoanalyzer could not be easily altered for use in the control system, the recorder was modified by attaching a logarithmic cam to the drive shaft and a pneumatic position indicator was used to generate a linear concentration signal.

The chemical addition was to take place in the aeration tank which required that the flow for use in the control system be the sum of the plant flow plus the return sludge flow. The return sludge flow was normally controlled as a percentage of the plant flow and since a reliable totalizer with which to combine these two flows was not available, it was decided to use the total plant flow without the return sludge flow. The error introduced by this action was corrected for the most part by adjustment of the controls

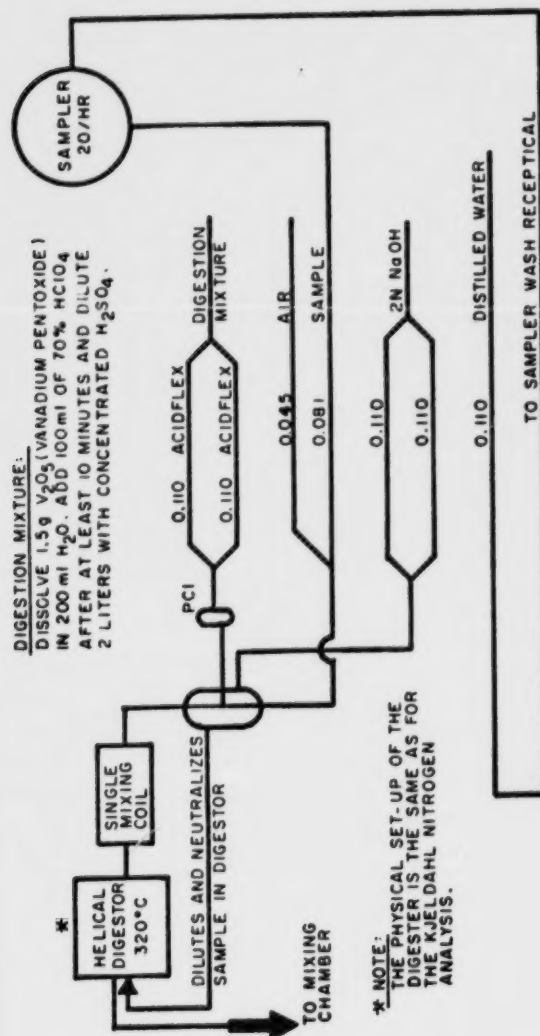


FIGURE 3
 TOTAL PHOSPHATE MANIFOLD - PUMP I

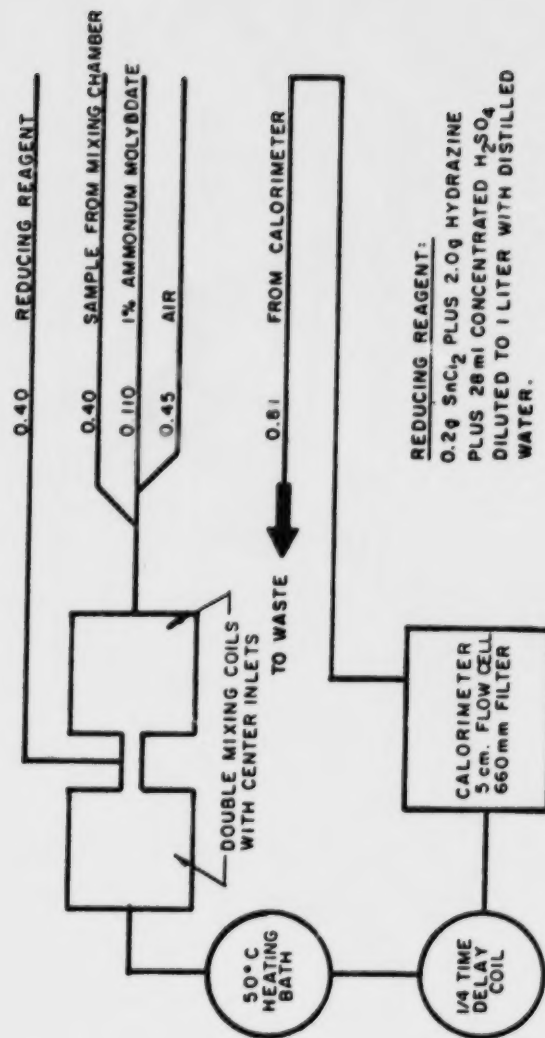


FIGURE 4
TOTAL PHOSPHATE MANIFOLD - PUMP 2

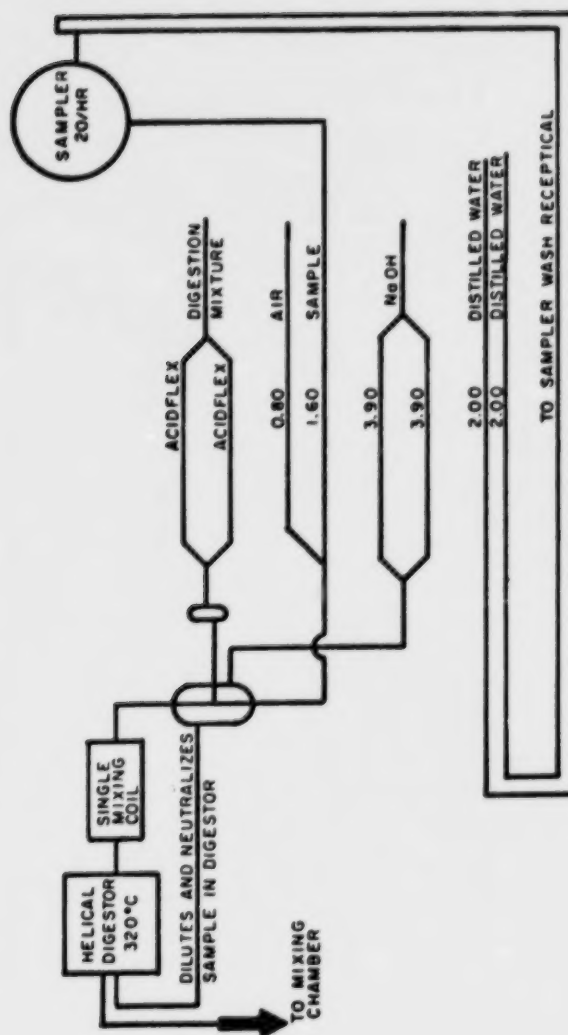


FIGURE 5
NEW TOTAL PHOSPHATE MANIFOLD - PUMP I

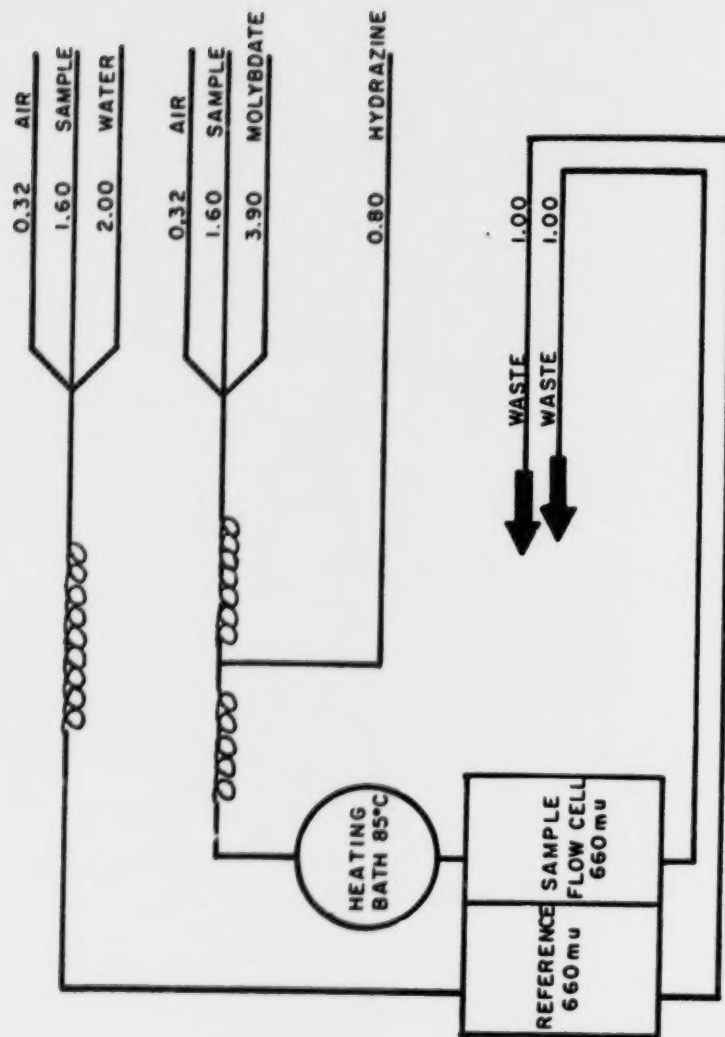


FIGURE 6
NEW TOTAL PHOSPHATE MANIFOLD - PUMP 2

Table 3. TOTAL PHOSPHATE ANALYZER REAGENTS

A. Digestion Mixture per liter

0.75 g V_2O_5

50 ml $HClO_4$

100 ml H_2O

Weigh out V_2O_5 into beaker (up to 4 liters)

Add water and allow to stand for 10 minutes.

Add $HClO_4$ then carefully add H_2SO_4 .

When the solution is cool (6 hours) bring to the desired volume with sulfuric acid. For analysis dilute two parts digestion mixture with one part distilled water.

Four liters are needed for each day's run.

B. Ammonium Molybdate (1%) (in 35 g) (3500 ml)

Dissolve 10 g of ammonium molybdate per liter of distilled water. Add 1 ml Levor IV wetting agent per liter.

C. Sodium Hydroxide

A stock solution of 40% NaOH is prepared by dissolving 400 g NaOH per liter. The working solution is prepared by diluting 140 ml of the stock to 1 liter.

D. Reducing Reagent

.2000 g $SnCl_2$

2.0000 g Hydrazine

28 ml H_2SO_4

Put solid reagent in 1 liter volumetric flask and fill half way with distilled water. Add H_2SO_4 and dilute to volume.

E. 1000 ppm Phosphorus standard

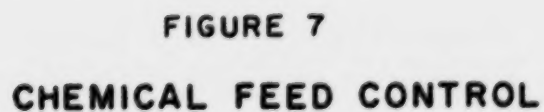
(5.6234 g K_2HPO_4 diluted to 1 liter)

on the chemical feed control system.

The plant flow signal was combined with the phosphorus signal with a Foxboro pneumatic multiplier. This product could be adjusted using a Moore ratio relay to provide a flexible chemical to phosphorus feed ratio. The ratioed signal was fed to a Foxboro flow controller which controlled the position of an air operated diaphragm valve. Chemical flow rates were measured by a chemically resistant rotometer and this signal provided feed back to the flow controller. The chemical was delivered to the aeration tank by means of a centrifugal pump in the case of the ferric chloride test and by air pressure in the case of the alum test.

The entire control system with the exception of the rotometer and the diaphragm control valve was mounted inside a weatherproof cabinet. The mixed liquor sample was pumped to an overflow pot inside the cabinet for sampling by means of a centrifugal pump which was mounted in the cabinet. A schematic diagram and pictures of the chemical feed control system are shown in Figures 7 to 9.

The unit was regularly calibrated by introducing a series of standard solutions into the analytical stream after first setting the base line using distilled water. During operation of the unit, baseline drift occurred as a result of a variation in the quantity of colloidal suspended solids which passed through the automatic filter. Adjustment of the baseline to correct for this residual turbidity was accomplished by introducing distilled water in place of the ammonium molybdate reagent. There was a very slow change in the residual turbidity with time and, as a consequence, the baseline was adjusted twice daily. A baseline reading was obtained by replacing the ammonium molybdate reagent with distilled water. Following adjustment of the baseline, the ammonium molybdate was reintroduced to the analytical stream and automated control was resumed. This procedure required approximately fifteen minutes.



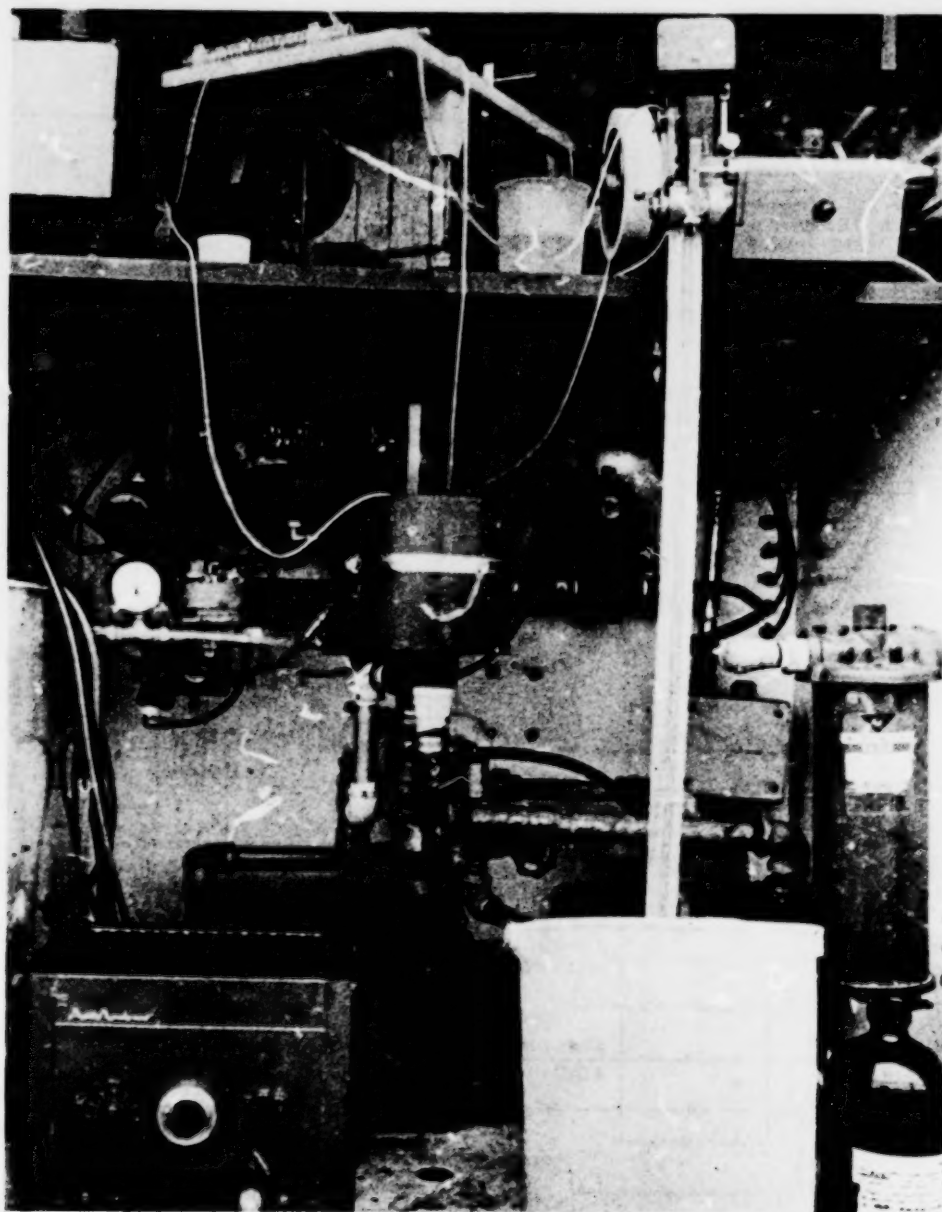


Figure 8
Chemical Control Feed System

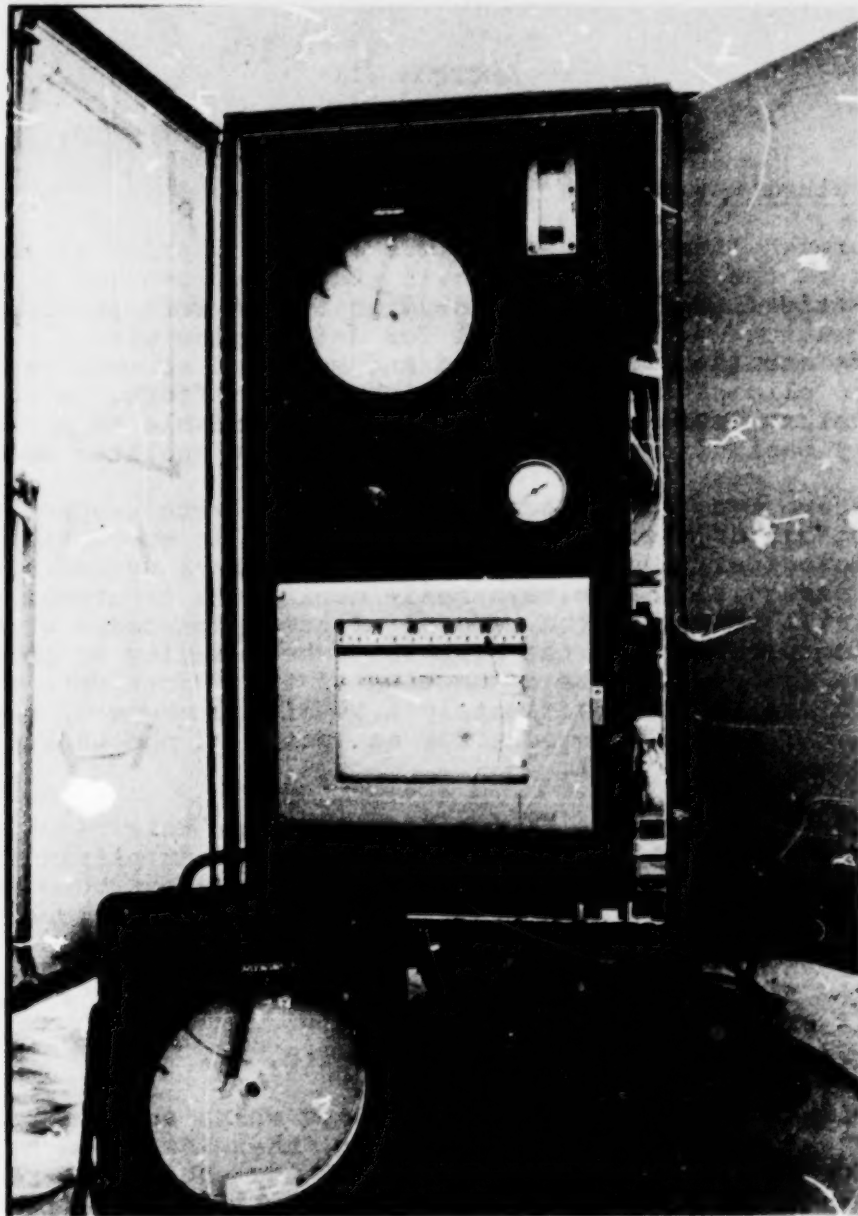


Figure 9
Chemical Control Feed System

SECTION VII

BIOLOGICAL REMOVAL STUDIES

Literature Review

A thorough literature search was conducted prior to the start of the biological removal studies to provide a firm theoretical base for these studies. This work provided information which was useful for determining what parameters should be investigated and measured as well as helping to eliminate needless duplication of effort. A complete literature review was written and is available on a temporary basis from the Municipality of Metropolitan Seattle.

There are two general schools of thought with respect to biological or natural phosphorus removal in excess to physiological requirements of the biological system (5-45). Both recognize that biosynthesis during the treatment process will result in the removal of some phosphorus which is incorporated into the biomass. The quantity of phosphorus removed will be a function of the growth rate and should represent approximately 1.5% of the new cell mass. This will normally account for an uptake of phosphorus in the range of 1-3 mg/l.

Additional phosphorus removal in excess of this natural uptake has been reported at several treatment plants throughout the country. (1, 2, 8-16). This uptake has been attributed variously to either biological uptake in excess of physiological requirements, the so called "luxury uptake", and to chemical precipitation of the phosphorus with one or more naturally occurring cations in the sewage followed by removal through adsorption and entrapment in the aeration and secondary clarification units.

Experimental data have been collected which support both of these hypotheses. In many cases, these data can be used in support of either hypothesis with the subsequent result that no clearcut conclusion has been arrived at. It seems likely that either, both or neither mechanism may be operable at any given plant. As a consequence, individual evaluation of the conditions at each treatment facility is required to assess the most promising approach for maximizing the "natural" biological removal of phosphorus.

Biological Full Scale Tests

Full scale plant testing based on the results of bench and jar scale tests, which are available from Metro upon request,

were conducted in an attempt to maximize the naturally occurring phosphorus removal in the activated sludge system. Absolute control of most variables was difficult to achieve in the operating facility although the degree of variability for parameters such as dissolved oxygen, suspended solids and detention time was minimized through operational controls at all times that tests were being run. This required special operating procedures regarding aeration rates, return activated sludge rates and wasting rates. Each of these variables were strictly controlled through directives from the laboratory.

It was decided early in the project that a complete mathematical analysis of all pertinent full-scale data would be necessary if any valid conclusions were to be drawn concerning biological removal of phosphorus. Statisticians from R. W. Beck and Associates, and the University of Washington helped develop the sampling and analyses techniques to insure that the raw data would be consistent and furnish valid information for statistical analysis. The variables selected for sampling and analysis are listed on Table 4.

A period of one week of operation under the selected conditions was allowed before each sampling period. This was done to develop as stable a sludge condition as possible before analysis was begun. The points at which samples were taken are shown in Figure 10.

Grab samples were collected at 2-hour intervals during the seven day studies, and brought to the laboratory for immediate analysis, according to the techniques described in the Materials and Methods section of this report.

Full scale plant operational reports using data obtained from routine sampling at the treatment plant were produced using a computer. These were two-page reports including the basic data and several calculated parameters chosen to outline the biological treatment process. Linear correlation and scatter plots were used as the first step in evaluating these data. Time relation diagrams, consisting of plots of each variable against time, were also used to examine the variability of each parameter. Cross correlation tables containing simple linear correlation coefficients for every possible combination of pairs of variables were developed to provide a concise way of reviewing all the correlation coefficients.

**Table 4. VARIABLES USED IN THE FULL-SCALE
BIOLOGICAL TESTS**

1. Primary Effluent Biochemical Oxygen Demand(BOD) - mg/l
2. Primary Effluent Phosphorus - mg/l
3. Return Activated Sludge Phosphorus - mg/l
4. Effluent Collection Chamber Phosphorus - mg/l
5. Final Effluent BOD - mg/l
6. Final Effluent Phosphorus - mg/l
7. Settling - mg/l
8. Mixed Liquor Suspended Solids - mg/l
9. Primary Effluent Calcium - mg/l
10. Primary Effluent Magnesium - mg/l
11. Final Effluent Calcium - mg/l
12. Final Effluent Magnesium mg/l
13. Total Plant Flow - mg/l
14. Air Applied - 1000 CFM
15. Waste Activated Sludge Flow - MGD
16. Return Activated Sludge Flow - MGD
17. Primary Effluent Phosphorus - lbs.
18. Effluent Collection Chamber Phosphorus - lbs.
19. Waste Activated Sludge Phosphorus - lbs.
20. Total Output Phosphorus - lbs.
21. Phosphorus Accounted for - lbs.
22. Percent Phosphorus Removed Secondary Process
23. Calcium Removed - lbs.
24. Magnesium Removed - lbs.
25. Lbs. BOD/lb. Solids Under Aeration
26. Cu. Ft. Air/gallon
27. Sludge Volume Index
28. Percent Total Phosphorus Removed
29. Total Phosphorus Removed - lbs.

- ① PRIMARY EFFLUENT
- ② RETURN ACTIVATED SLUDGE
- ③ MIXED LIQUOR
- ④ EFFLUENT COLLECTION CHAMBER
- ⑤ EFFLUENT AFTER CHLORINATION

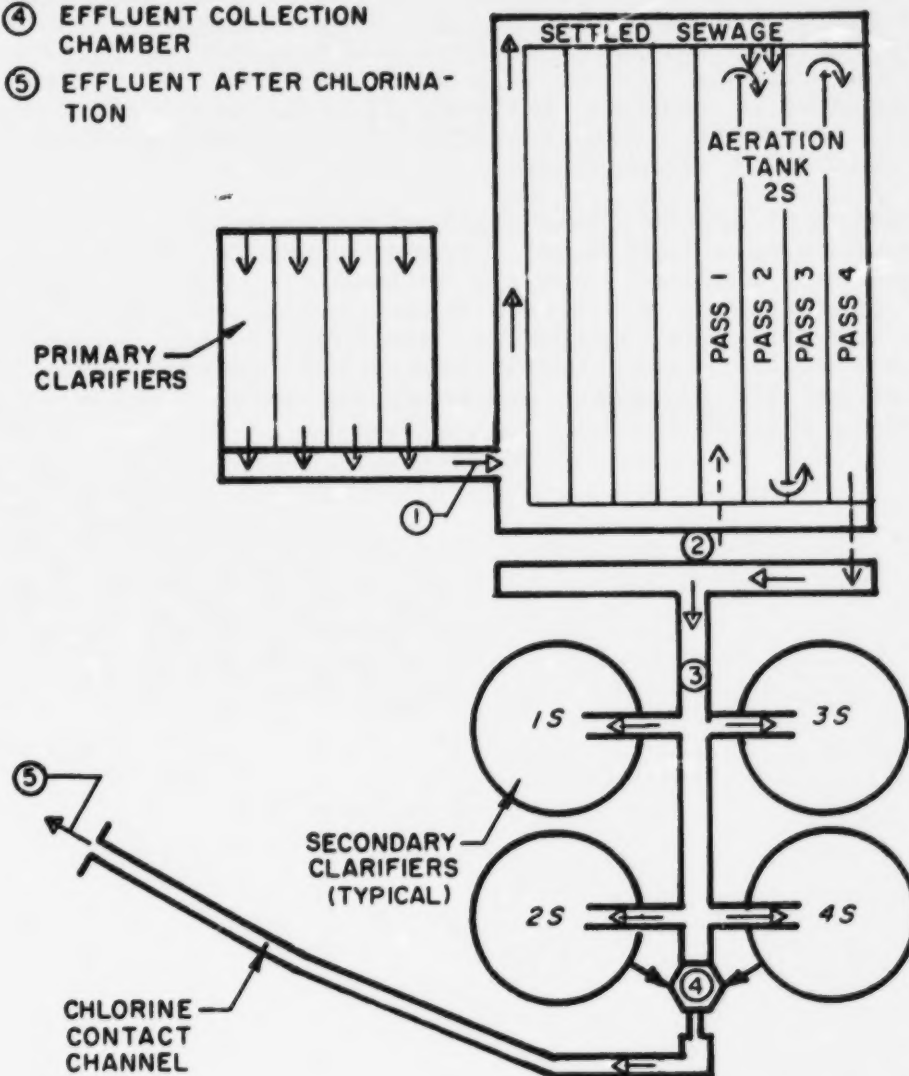


FIGURE 10
FULL SCALE BIOLOGICAL TEST SAMPLING POINTS

Stepwise multiple linear regression methods were initiated for the examination of more complex relationships than simple two variable situations. Results from simple linear investigations and scatter plots were helpful in evaluating the possible usefulness of multiple linear methods. Analysis of Variance was employed to determine whether variation in a parameter was of a level of significance beyond that expected by chance. Analysis of Covariance provided the same information with the added facility of removing known sources of variability.

The results of all of these statistical analyses are available upon request from Metro. The programs for these analyses were obtained from the "Biomedical Computer Programs" published by the Health Sciences Computing Facility of the University of California, Los Angeles (46). Samples of operational reports, linear correlation scatter plots and time relation diagrams are shown in Tables 5 and 6 and Figures 11 through 13.

MONDAY
10/26/70

Table 5. METRO RENTON PLANT FULL SCALE
PLANT PHOSPHORUS REMOVAL WEEKLY

PROG NO. R01-1
INPUT WPC R00
10/26/70
DATE RUN 02/12/71
PAGE 1

HR	PRIMARY EFFLUENT		ACTIVATED SLUDGE		COLL. CHAMBS.		FINAL EFFLU.		SETTL- ING	MIX LIQUOR SUSP SOLIDS		PRIM.		FINAL PLANT		TOT. FLOW	AIR APPL- IED		WASTE ACT SLUDGE		RETURN ACT SLUDGE FLOW
	BCD	PHOS	PHOS	PHOS	PHOS	BOD	PHOS	ML/L		MG/L	MG/L	MG/L	MG/L	MG/L	MGD		CPM	MGD	MGD		
1	80	9.4	88	10.4	7.7	11.7	462	1552	15.0	4.3	16.0	4.5	13.0	23.0	0.10	9.2					
2	95	9.6	87	10.2	7.5	11.3	431	1485	15.0	4.4	16.0	4.5	15.0	23.0	0.10	6.0					
3	110	9.8	86	10.0	7.4	10.8	406	1438	15.0	4.5	16.0	4.5	12.0	23.0	0.10	4.8					
4	108	9.1	84	9.7	7.1	10.2	334	1428	16.5	4.8	16.0	4.5	21.0	23.0	0.10	8.4					
5	106	8.5	84	9.3	7.9	9.9	356	1416	18.0	5.2	16.0	4.5	26.0	23.0	0.10	10.4					
6	109	9.5	84	9.0	9.7	9.7	320	1400	17.5	5.1	16.0	4.5	21.5	23.0	0.10	11.4					
7	112	10.5	85	8.6	11.0	9.4	330	1405	17.0	5.0	16.1	4.5	20.0	23.0	0.10	11.6					
8	115	11.0	86	8.8	11.0	9.1	339	1417	18.0	5.0	16.4	4.5	20.0	23.0	0.10	11.2					
9	118	11.5	92	8.9	11.0	9.2	333	1470	19.0	5.0	16.7	4.5	20.0	23.0	0.10	10.4					
10	116	10.5	100	8.9	11.0	9.5	334	1521	17.5	4.8	17.0	4.7	25.0	23.0	0.00	11.2					
11	114	9.5	100	8.4	13.2	8.9	345	1580	16.0	4.7	16.4	4.6	25.0	23.0	0.00	11.2					
12	127	9.6	100	6.5	14.9	8.3	374	1601	16.5	4.7	16.0	4.5	24.0	23.0	0.00	10.0					
13	140	9.8	99	5.3	14.4	7.0	419	1584	17.0	4.7	16.0	4.5	22.5	23.0	0.00	9.9					
14	149	10.3	98	4.8	13.5	6.0	413	1570	17.5	4.7	16.0	4.5	22.0	23.0	0.00	10.6					
15	158	10.9	99	4.7	11.3	5.7	391	1557	18.0	4.7	16.0	4.5	23.5	23.0	0.00	10.3					
16	147	11.2	102	5.4	9.0	5.4	437	1537	17.5	4.6	16.0	4.5	24.0	23.0	0.00	10.3					
17	136	11.5	127	6.2	9.0	6.0	552	1511	17.0	4.6	16.0	4.5	23.5	23.0	0.00	10.6					
18	130	11.5	133	6.9	9.0	6.4	585	1515	17.0	4.5	16.0	4.5	23.5	23.0	0.00	10.6					
19	124	11.5	137	7.0	10.6	6.8	570	1540	17.0	4.5	16.0	4.2	19.0	23.0	0.00	8.5					
20	126	11.2	156	7.0	12.0	7.0	504	1531	17.0	4.5	15.7	4.1	17.0	23.0	0.00	7.6					
21	128	11.0	156	7.0	12.0	7.0	481	1564	17.0	4.5	15.4	4.1	16.0	23.0	0.00	7.2					
22	127	11.0	142	7.3	12.0	7.0	474	1549	17.0	4.5	15.0	4.0	14.5	23.0	0.00	6.5					
23	126	11.0	129	7.4	12.0	7.0	456	1504	18.0	4.4	15.0	4.0	11.0	23.0	0.00	4.9					
24	130	10.0	136																		
MINIMUMS, MAXIMUMS, AVERAGES																					
80	8.5	84	4.7	7.1	5.4	320	1400	15.0	4.3	15.0	4.0	11.0	23.0	0.00	4.8						
158	11.5	156	10.4	14.9	11.7	693	1601	19.0	5.2	17.0	4.7	29.0	23.0	0.10	11.6						
122	10.4	108	7.7	10.7	9.2	433	1509	17.0	4.7	16.0	4.4	21.3	23.0	0.04	9.2						

MONDAY
10/26/70

Table 6. METRO RENTON PLANT FULL SCALE
PLANT PHOSPHORUS REMOVAL WEEKLY

PROG NO. R01-1
INPUT WPC NO0
10/26/70
DATE RUN 02/12/71
PAGE 2

	PRIM EFFL PHOS	EFFL CHAMB. PHOS.	WASTE ACTIVAT. SLUDGE PHOS	TOTAL OUTPUT PHOS	PHOS ACCT.'d FOR	% PHOS REMOVED SECOND, PROCESS	REMOVED CA	LB BOD/ LB SOLIDS UNDER AERATION	CU FT AIR/ GAL./ DAY	SLUDGE VOL. INDEX	TOTAL % PHOS. REMOVED	TOTAL PHOS RE- MOVED	
HR	LB	LB	LB	LB	LB	LB	LB					LB	
1	1019	1128	73	1269	1201	7.20	-108.4	-21.7	0.06679	1.020	298	-24.47	-249
2	1201	1276	73	1414	1349	6.04	-129.1	-12.5	0.09563	1.577	290	-17.71	-213
3	981	1001	72	1081	1073	7.31	-100.1	0.0	0.09149	1.971	262	-10.20	-100
4	1594	1699	70	1786	1769	4.40	97.6	52.5	0.15830	1.127	269	-12.09	-193
5	1843	2017	70	2147	2087	3.80	433.7	130.1	0.19400	0.910	251	-16.47	-304
6	2258	2139	70	2306	2209	3.10	356.5	118.8	0.22117	0.830	229	-2.11	-43
7	2540	2126	71	2273	2199	2.79	217.7	96.7	0.23042	0.816	235	10.48	266
8	2569	2055	72	2125	2127	2.79	373.6	93.4	0.22650	0.845	239	17.27	444
9	2494	1930	77	1995	2007	3.08	498.7	65.1	0.20802	0.910	227	20.00	499
10	2139	1856	0	1981	1856	0.00	104.2	20.3	0.19004	0.915	220	9.52	208
11	1981	1751	0	1856	1751	0.00	-03.4	20.9	0.17979	0.915	218	6.32	125
12	1922	1301	0	1661	1301	0.00	100.1	40.0	0.18976	0.952	234	13.54	260
13	1839	995	0	1314	995	0.00	187.6	37.5	0.19821	1.016	265	28.57	525
14	1890	881	0	1101	881	0.00	275.2	36.7	0.20811	1.038	263	41.75	789
15	2136	921	0	1117	921	0.00	392.0	39.2	0.23769	0.971	251	47.71	1019
16	2242	1081	0	1031	1081	0.00	300.2	20.0	0.22879	0.952	284	51.79	1161
17	2302	1241	0	1201	1241	0.00	200.2	20.0	0.21531	0.952	765	47.83	1101
18	2254	1352	0	1254	1352	0.00	196.0	0.0	0.20999	0.971	386	44.35	1000
19	2158	1314	0	1276	1314	0.00	187.6	37.5	0.18958	1.016	370	40.37	832
20	1775	1109	0	1109	1109	0.00	158.5	47.5	0.15495	1.204	450	37.50	666
21	1560	992	0	992	992	0.00	184.3	56.7	0.14166	1.346	329	36.36	567
22	1468	934	0	934	934	0.00	213.5	53.4	0.12950	1.428	308	36.36	534
23	1330	883	0	847	883	0.00	241.9	60.5	0.11756	1.577	306	36.36	484
24	917	679	0	642	679	0.00	275.2	36.7	0.09477	2.083	303	30.00	275
MINIMUMS, MAXIMUMS, AVERAGES													
	917	679	0	642	679	0.00	-125.1	-21.7	0.06679	0.816	218	-24.47	-304
	2569	2139	77	2306	2209	7.31	498.7	130.1	0.23769	2.083	450	51.79	1161
	1852	1361	27	1448	1388	1.09	190.3	43.8	0.17333	1.173	286	19.73	404

10/ 25/ 70
DATE RUN 03/ 02/ 71

METRO RENTON PLANT
OPERATIONAL DATA
TIME RELATION DIAGRAM - WEEKLY

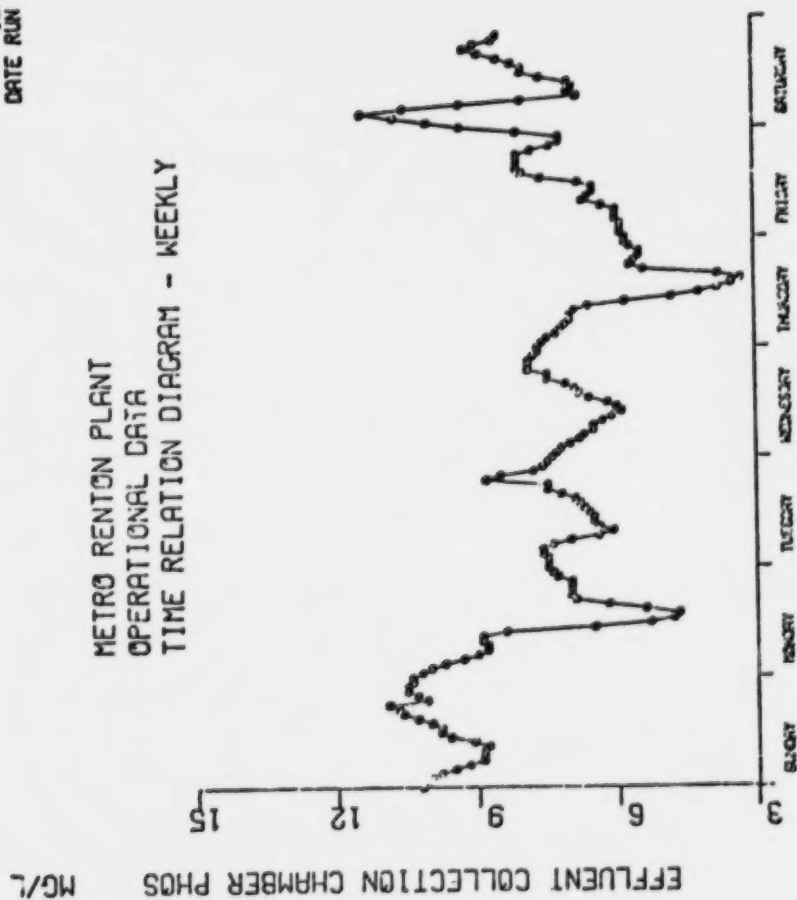


FIGURE II
TIME RELATION PLOT

10/ 25/ 70
DATE RUN 03/ 02/ 71

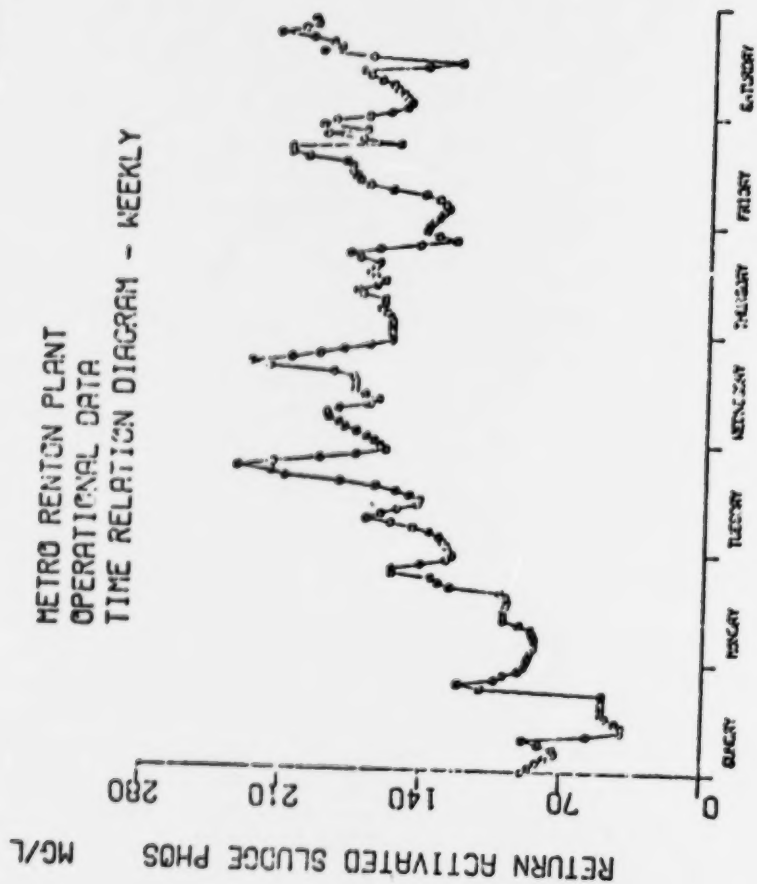


FIGURE 12
TIME RELATION PLOT

8/ 4/ 70 - 8/ 10/ 70

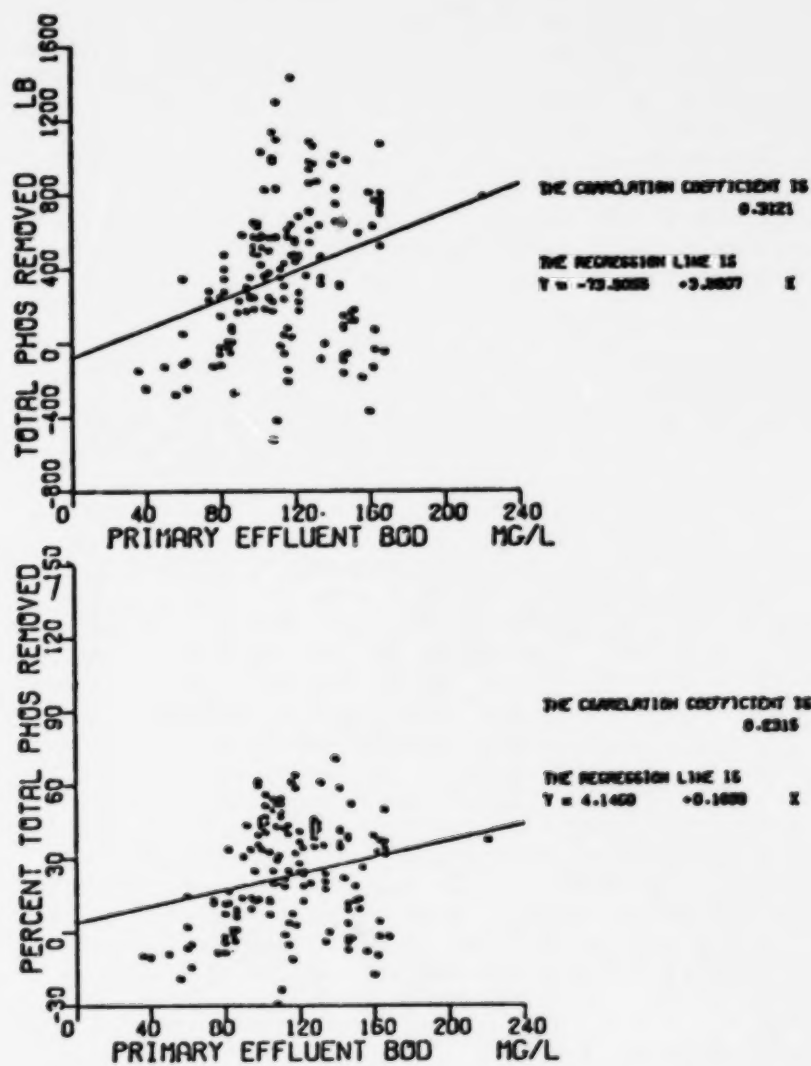


FIGURE 13
LINEAR COORELATION SCATTER PLOTS

The first series of tests was designed to study the effect of feed method and solids concentration on phosphorus removal. The combinations that were tried were plug feed-low mixed liquor suspended solids concentration, plug feed-high mixed liquor solids concentration, step feed-low mixed liquor solids concentration and step feed-high mixed liquor solids concentration. Each of these tests involved a minimum of one week of operation at the desired conditions before sampling was begun. Samples were collected and analyses run every two hours for a period of seven days. The average results of these tests are shown on Table 7. Complete results can be obtained from Metro on a loan basis.

Examination of Table 7 suggests that the removal of phosphorus is directly dependent on the organic loading and thus in theory on the biological growth. The pounds of BOD per pound of mixed liquor solids during the first test was twice that of the second test while the percentage and pounds of phosphorus removed were also doubled. The step aeration period shows that removal was better in the low suspended solids test when the loading was slightly higher and the wasting rate was significantly higher than during the high solids test. These facts all agree with the assumption that a large biological growth is necessary to promote biological inclusion of phosphorus. This suggests that both the loading and waste rates must be controlled to obtain high biological phosphorus removal. An attempt was made to determine the pounds of volatile solids produced per day to correlate this value with the phosphorus removal. The results which are shown in Table 7 are not completely consistent since test #2 shows a high solids production combined with a low phosphorus removal. This discrepancy was most likely related to errors in the measurement of waste sludge flow which resulted in inaccurate estimates of the pounds of sludge produced. Variations in the percent of phosphorus contained in the sludge could also account for part of the apparent inconsistency.

As a consequence of these results, a full scale plant experiment was designed so that a hypothesis concerning controllable plant parameters could be tested. The hypothesis was that waste activated sludge flow and aeration rate had an effect upon the biological uptake of phosphorus. These two parameters are often used to control the secondary process so their importance in an operational model, if one could be constructed, is evident.

These two variables are the only two of the twenty-nine variables examined in this project which can be completely controlled by plant personnel. They had not, however, been

Table 7. AVERAGE RESULTS OF FULL SCALE FEED AND MIXED LIQUOR SOLIDS CONCENTRATION TESTS

TEST NO.	OPERATION MODE	PRIM. EFF.		FINAL EFF.		MLSS mg/l	Plant Flow MGD	AIR l/c00 cfm	Waste Rate MGD	Return Rate MGD	lb. BOD 5 MLSS	SVI	% PHOS Rem.	lb PHOS Removed/Day	lb. VSS Produced/Day
		BOD mg/l	PHOS mg/l	BOD mg/l	PHOS mg/l										
1	Plug Flow Low MLSS	119	7.12	9.0	7.52	1497	20.36	23.0	0.044	8.7	0.161	312	25.76	468	4,863
2	Plug Flow High MLSS	80	9.55	3.2	8.30	2376	2175	35.2	0.05	10.0	0.08	131	13.18	212	6,038
3	Step Aeration Low MLSS	113	12.7	7.1	8.24	1789	2475	17.5	0.09	8.33	0.123	148	38.88	929	12,476
4	Step Aeration High MLSS	116	10.0	9.0	7.80	2016	19.94	22.8	0.04	9.00	0.119	167	23.05	376	3,693

controlled in any systematic way before this experiment was defined, but had always been changed manually or automatically in response to conditions in the plant. This eliminated any possibility of determining if a change in another variable was due to the fact that one of these controllable variables had been changed.

The goal of the experiment was to observe the effect upon the system when these two variables were changed in a systematic manner. In light of this, the experiment was designed so that sampling could occur during periods when these two variables were held constant. The variables were assigned values corresponding to three levels; low, medium, and high since the absolute values would not be relevant to any other plant while the relative values could be applied to other plants in conjunction with operational data.

Each combination was held constant for seven days beginning on Friday. Samples were collected and analyzed for all variables on the following Wednesday and Thursday. The sampling procedures for this experiment were almost the same as for the weekly sampling schedule except that samples were collected hourly instead of every other hour.

The results of this experiment were reported in plant reports with exactly the same format as the weekly reports. The raw data can be obtained on loan from Metro. Table 8 shows the nine experimental conditions and the average percent total phosphorus removed for each sample period. It was discovered after setting up for the combination of a low air and low waste rate that it was not possible to operate the treatment plant under these conditions. The high solids concentration resulting from the low waste rate in combination with the low aeration rate resulted in inadequate oxygen concentrations in the aeration tank. Therefore, operation under this set of conditions was discontinued before the equilibration period was completed. The test involving medium air and low waste was not completed for the same reason.

Standard statistical methods were not applied to the data since the experimental series could not be completed. There is a great deal of variability in the data which makes it difficult to come to any substantial conclusions without the use of these methods. The experiment did, however, demonstrate several things. As noted in Table 8, a consistent increase in removal was recorded from Wednesday to Thursday. Also there was better phosphorus removal at higher aeration and wasting levels with an increase in the aeration rate appearing to make a greater difference. It

Table 8. Mean Percent Total Phosphorus Removed
On Wednesday and Thursday

Air cu. ft./ gal. Waste Activated Sludge lbs/day	Low	Medium	High	Day
	0.72 cu.ft. per gallon	0.86 cu.ft. per gallon	1.0 cu.ft. per gallon	
Low 2,816	----	-----	34.7	Wed.
	----	-----	41.7	Thurs.
Medium 7,400	16.8	40.4	40.1	Wed.
	36.0	42.5	50.7	Thurs.
High 14,000	24.8	28.4	48.6	Wed.
	39.4	35.6	44.4	Thurs.

was not possible to make any definite conclusions because of the amount of variability in the values and as a result of our inability to treat the data statistically. If the experiment could have been replicated so that several values were available for each set of conditions, statistical methods would have been applied to the data to see if the observed trends are meaningful.

In addition to the special sampling tests, normal sampling and analysis of plant composite samples was conducted on a routine basis during the period of the grant. Primary effluent and final effluent samples were composited on a flow paced basis by automatic samplers. The mixed liquor, return activated sludge and effluent collection chamber samples were hand composited on a time basis by the plant operators. All samples were stored at 4°C after collection.

The variables shown on Table 5 page 32 were analyzed daily over a period of eleven months. The daily averages for the period December 1970 through April 1971, which can be obtained from Metro, were selected for statistical evaluation. It was felt that these data were the most valid as a result of the valuable experience which had been gained in collecting data prior to these dates.

Of the analyzed variables, only five were controllable by plant operators. These were:

1. Return Activated Sludge Flow
2. Mixed Liquor Suspended Solids Concentration
3. Air Applied
4. Waste Activated Sludge by flow
5. Lbs. BOD/lb. Solids Under Aeration

To establish the importance of these variables to the biological uptake of phosphorus, a regression analysis was employed. This method successively adds each variable to a regression equation according to its mathematically determinable importance in explaining variability in the dependent variable, which was in this case the effluent collection chamber phosphorus. This variable was determined to be the best indicator of the biological removal of phosphorus on the basis of the analyses which had previously been performed during the research project. Regression analysis showed that the controllable variables had the following order of importance:

1. Return Activated Sludge Flow
2. Waste Activated Sludge Flow
3. Air Applied
4. Mixed Liquor Suspended Solids Concentration
5. Lbs. BOD/lb. Solids Under Aeration

However, three-fourths of the variability in the effluent collection chamber phosphorus was still unexplained after these variables were introduced into the regression equation. The failure to fully explain the variability in the effluent collection chamber phosphorus implies that a large part of this variability was due to factors which were not included in the regression analysis. Identification of these factors will be of significant importance if more complete control of the biological phosphorus removal is to be achieved.

An examination of the data generated during this phase of the grant showed that there was a weekly cycle in the phosphorus removal as well as in the primary BOD and the calcium and magnesium removals. The phosphorus and calcium removal were greater and the calcium removal was less during the period Wednesday through Saturday than for the remainder of the week. This cycle was statistically analyzed using the Analysis of Variance. The average values during the two periods as well as the results of the statistical analysis are presented in Table 9.

As the table shows, phosphorus removal, magnesium removal, and the primary BOD were greater, while primary phosphorus, effluent phosphorus, and calcium removal were less during the Wednesday through Saturday period than during the Sunday through Tuesday period. All of these differences were statistically significant except for the calcium removal. The difference in phosphorus removal averaged 0.63 mg/l which corresponds to an increase in the secondary phosphorus removal from 20.6% on the Sunday through Tuesday period to 29.8% on the Wednesday through Saturday period. This represents a net increase in the quantity of phosphorus removed of 42% during the Wednesday through Saturday period.

The failure of the calcium removal cycle to coincide with the phosphorus removal cycle makes it extremely unlikely that the removal is chemical in nature. The correlation between magnesium removal and phosphorus removal is in agreement with the work reported by the City of Baltimore (10) and Olson, et al. (13). The fact that the increases in magnesium and phosphorus removal occur in conjunction with an increase in the BOD entering the aeration system strongly suggests that the phosphorus removal is biological in nature. The inability to account for more than 25% of the variability in the phosphorus removal indicates either that factors other than those which were considered exert a considerable effect on the biological removal or that the statistical methods used were inadequate for examining biological phenomenon.

Table 9. CYCLIC VARIABILITY OF SELECTED PARAMETERS
AND THE STATISTICAL SIGNIFICANCE OF THIS VARIABILITY

VARIABLE	SUN-TUES Average mg/l	WED-SAT Average mg/l	F-FACTOR 3.9 sig. 95%
Primary Phosphorus mg/l	7.29	6.79	6.396
Primary BOD ₅ mg/l	76.8	93.2	15.226
Primary Calcium mg/l	15.49	15.89	5.145
Primary Magnesium mg/l	6.91	6.88	.024
Effluent Phosphorus mg/l	5.79	4.66	16.753
Final Calcium mg/l	15.07	15.72	12.301
Final Magnesium mg/l	6.72	6.35	5.647
Calcium Removed mg/l	0.42	0.17	2.318
Magnesium Removed mg/l	0.21	0.55	4.170
Calcium Removed percent	1.3	1.07	2.000
Magnesium Removed percent	3.3	8.0	4.915

SECTION VIII

CHEMICAL REMOVAL

Chemical Removal Literature Review

As was the case for the biological removal studies, a thorough literature search was conducted on chemical phosphorus removal prior to the inception of the experimental work. A complete literature review was written and is available from Metro on a temporary basis.

All chemical removal schemes depend upon the formation of an insoluble cation - phosphate compound which can subsequently be removed by a physical separation process. The selection of the appropriate cation for use in this procedure must be based on a number of criteria including availability, ease of use, lack of toxicity and, ultimately, economics. The four cations which most closely meet these criteria are aluminum in the +3 oxidation state, iron in either the ferrous or ferric state and calcium.

In addition to the choice of chemical, there is also a choice of chemical addition point. There are three basic schemes for phosphorus removal which have been investigated (47-130). These are: (1) addition of the chemical to the raw sewage followed by the combined removal of raw and chemical sludge in the primary clarifiers, (2) addition of the chemical to the biological treatment system followed by removal of the precipitated phosphorus in the waste activated sludge, and (3) tertiary removal in which the chemical is added to the secondary effluent and the precipitated phosphorus is removed by a subsequent physical separation process.

Each of these separation schemes has several variations and each offers distinct advantages as well as having distinct disadvantages. The major advantage of chemical addition to either the raw sewage or activated sludge is that it makes use of existing clarification units and thus does not require the construction of additional treatment facilities. Addition of the chemical to the activated sludge system places the further restraint on the chemical that it must not cause the system pH to vary outside the limits of the biological tolerances. Tertiary removal methods do not depend upon the removal efficiencies of the secondary clarifiers and have the additional advantage that they are dealing with a lower phosphorus concentration

due to the prior biological removal. The chemical requirements in that case may be lower than for the primary and activated sludge removal schemes.

One of the major problems associated with all of the chemical removal procedures is the additional sludge production. Of the suggested chemicals, only lime can be effectively recovered and reused. While this recovery and reuse does not alter the chemical costs, it does minimize the quantity of extra sludge being produced. Since effective phosphorus removal does not occur with lime until the pH exceeds 10, this alternative is not available for chemical addition to the activated sludge.

The major emphasis of this research work was directed toward the use of direct chemical addition to the activated sludge for phosphorus removal. On this basis, iron and aluminum salts offered the greatest opportunity for investigation. It was hoped that this approach would result in savings due both to the combined use of the secondary clarifiers for activated sludge and chemical sludge removal and to a reduction in the required chemical dosage as a result of natural biological phosphorus removal prior to the chemical addition.

Ionic Composition of Renton Wastewater

A series of analyses were performed to provide data regarding the ionic composition of the Renton wastewater since this data was necessary for the proper assessment of possible chemical reactions which might occur. The results of these analyses for the primary and secondary effluents are shown in Table 10. The anion deficiencies were assumed to correspond to the bicarbonate concentration which is in good agreement with the potentiometric titration data.

It was desired to measure the variation in the bicarbonate content of the effluent with time in order to determine if any correlation between bicarbonate and phosphorus removal existed. The bicarbonate concentrations were determined by potentiometric titrations. The validity of these titrations to accurately measure bicarbonate levels was proved by carrying out comparable titrations on a synthetic effluent which was prepared to replicate the ionic composition shown in Table 10. An example of the potentiometric titration plot is presented in Figure 14.

A series of samples were collected over a one week period including two intensive 24-hour samplings during which samples were collected every two hours. A plot of the data

Table 10. ION PROFILES

CATION PROFILE	PRIMARY EFFLUENT		FINAL EFFLUENT BEFORE CHLORINATION	
	ppm	meq/l	ppm	meq/l
Na	27.4	1.19	29.0	1.26
K	16.7	0.43	12.3	0.42
Mg	6.4	0.53	6.7	0.55
Ca	15.8	0.79	13.9	0.70
Fe	3.8	0.14	0.5	0.03
NH ₄ (as N)	21.8	1.56	11.0	0.79
	Total	4.64	Total	3.75

ANION PROFILE	PRIMARY EFFLUENT		FINAL EFFLUENT BEFORE CHLORINATION	
	ppm	meq/l	ppm	meq/l
PO ₄	33.2	0.52	24.4	0.38
SiO ₃	8.7	0.31	5.7	0.20
BO ₃	0.7	0.10	0.7	0.10
SO ₄	29.0	0.58	28.0	0.58
Cl	31.0	0.86	31.0	0.86
NO ₃ (as N)			2.4	0.17
	Total	2.37	Total	2.29

The Primary Cation/Anion balance shows a deficiency of 2.27 meq/l.

The Final Effluent Before Chlorination Cation/Anion balance shows a deficiency of 1.46 meq/l.

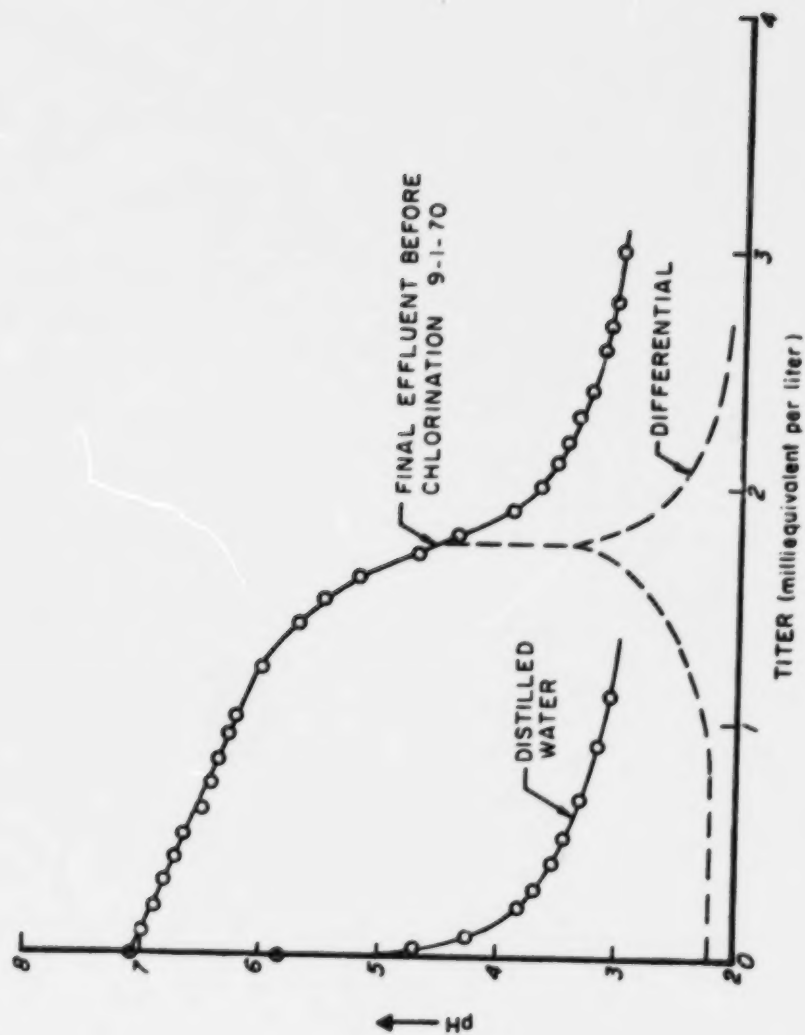


FIGURE 14
TYPICAL POTENTIOMETRIC TITRATION VERSUS
0.10N HCl AND END-POINT DETERMINATION

from the one week sampling period is presented in Figure 15.

Figure 16 shows the bicarbonate variation during the intensive two day sampling. The results of these tests indicate that there is a diurnal variation in the bicarbonate content of the effluent ranging from 1.35 to 2.0 milliequivalents per liter with a minimum occurring at approximately 1300 hours. This variation appears to correlate with the loading. There is no evidence to indicate that this variation is correlated with phosphorus removal.

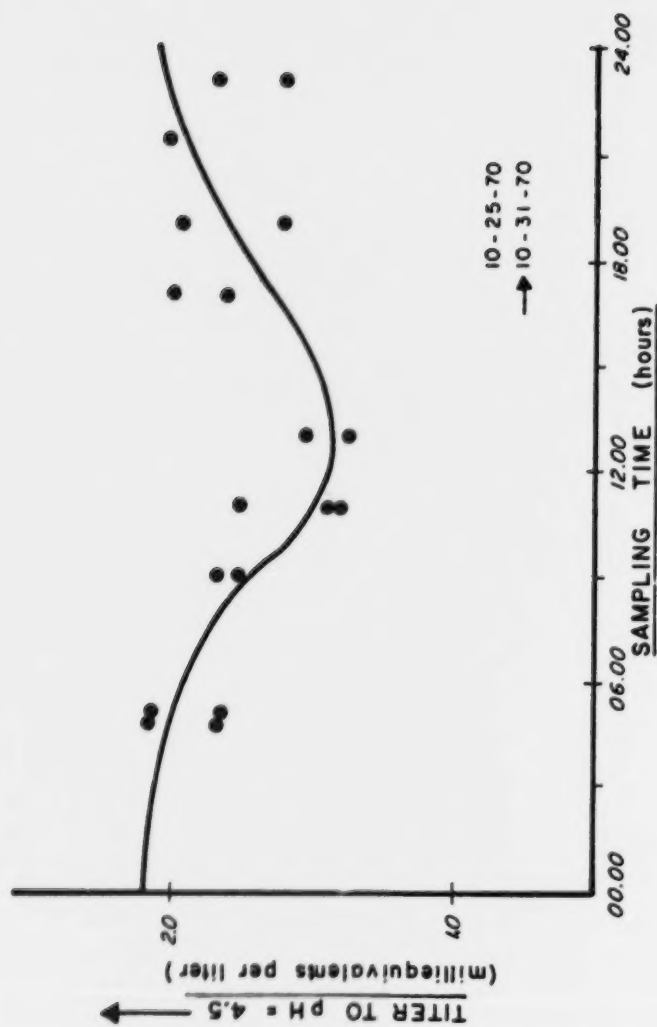


FIGURE 15
DIURNAL VARIATION IN BICARBONATE ASSAY

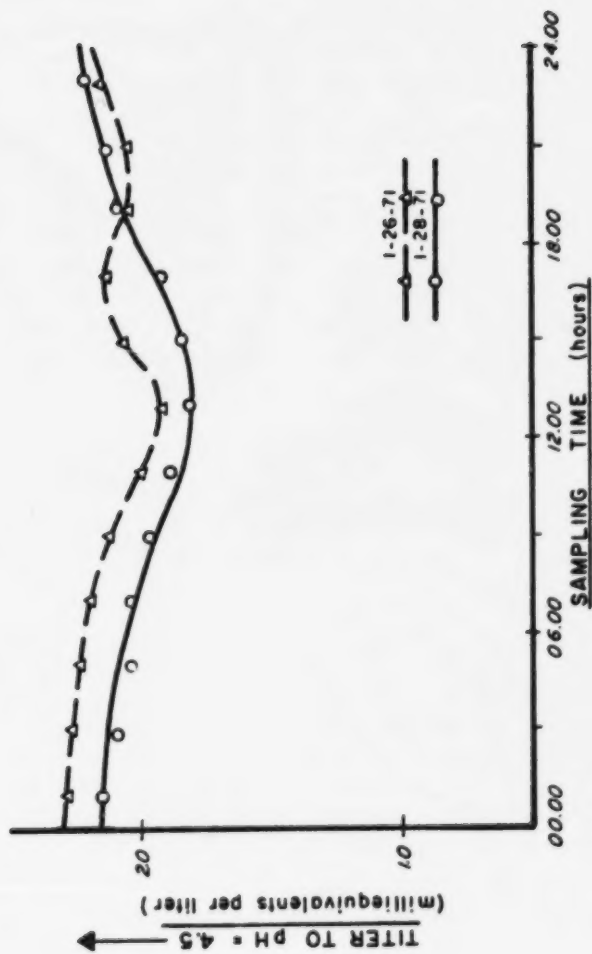


FIGURE 16
DIURNAL VARIATION IN BICARBONATE ASSAY - 24 HOUR TEST

Full Scale Studies

The first full scale test attempted to duplicate the results obtained at the Hyperion Treatment Plant (2). It was reported that consistent and repeatable high phosphorus removals could be obtained at the Hyperion Treatment Plant whenever conditions in the aeration system could be adjusted to achieve a pH rise in the aeration tank effluent and partial nitrification in the secondary. Establishment of these conditions at Hyperion required operation at plug flow, high aeration rate and high mixed liquor suspended solids levels in combination with an extended period of aeration (approximately 8 hours), and the discontinuation of digester supernate recycling.

The mechanism for this phosphorus removal was theorized to be a calcium phosphate precipitation made possible by the pH rise. The rise in pH was, in turn, proposed to be caused by a CO_2 stripping reaction which could occur only after the majority of the carbon metabolism had been completed(2). It was further proposed that the beginning of nitrification indicated that the carbonaceous demand had been satisfied and, as such, was a necessary condition for the pH rise.

The flow regime, mixed liquor suspended solids, and aeration rates were adjusted at the Renton treatment plant so as to approach as closely as possible conditions at the Hyperion plant. However, there were some limitations which prevented attainment of an exact duplication of these conditions.

There were two major differences which could easily have affected the outcome of this test. The first of these was the inability to provide a long aeration time. While the aeration time at the Hyperion plant was close to 8 hours, the maximum achievable aeration time at the Renton plant was 4 hours, and this only during the daily low flow periods. Even though a significant degree of nitrification was achieved (50% conversion of NH_3 to NO_3), a pH rise through the aeration system was not observed. This inability to obtain a pH increase at Renton was attributed to the short aeration time.

The second major difference was in the nature of the influent sewage which averaged 14 mg calcium per liter compared with a value of 56 mg calcium per liter for the Hyperion plant(2). Since the phosphorus removal mechanism proposed for the Hyperion plant involved a precipitation of

phosphorus as calcium phosphate, this difference was also significant. Jar scale tests, were conducted in an attempt to overcome the deficiencies in the full-scale tests. However, the results obtained at the Hyperion Treatment Plant could not be duplicated in either full or jar-scale tests. Subsequent efforts were therefore directed to full-scale testing of the effectiveness of chemical addition for phosphorus removal.

The addition of alum and ferric chloride at the end of the aeration tank was proposed to be the most effective procedure to follow during the full scale chemical feed studies on the basis of the jar-scale chemical tests and full-scale biological tests was to be controlled proportionally to the quantity of phosphorus present at the addition point. The major factor in the choice of the chemical addition point was the highly variable and unpredictable biological phosphorus removal in the aeration system. Addition of the chemical to the primary could not take this removal into account, which would have resulted in an inefficient use of the chemical. Since addition at the aeration tank outlet would occur following the biological phosphorus removal, this feed point would automatically compensate for any biological uptake and would therefore result in the most economical chemical usage.

The same general conditions were maintained throughout both tests. A description and schematic of the chemical feed control system which was used for both tests has been presented in the "Materials and Methods" section. Figure 17 shows a diagram of the aeration system with the relative position of the sampler-controller and the chemical addition point. The position of the sampler-controller was located upstream of the feed point to provide a detention time in the aeration tank between the sampling point and the feed point approximately equal to the time required to complete the automated phosphorus analysis.

The frequencies of analyses were changed with experience as it was determined that the initial analytical schedule could not be maintained due to the quantity of analyses required. Samples of primary effluent, mixed liquor, return activated sludge and final effluent were collected hourly and brought to the laboratory for analysis. Samples collected between 1800 and 0700 were stored in a 5°C refrigerator for analysis on the following day. Mixed liquor settling was run hourly by the operations crew on a portion of the samples which were delivered to the laboratory. Additional samples were collected at points A through E on Figure 17 every third hour (0900, 1200, etc.) for analysis of pH and alkalinity. Alkalinity was measured on the super-

- ① PRIMARY EFFLUENT
- ② MIXED LIQUID
- ③ RETURN ACTIVATED SLUDGE
- ④ FINAL EFFLUENT

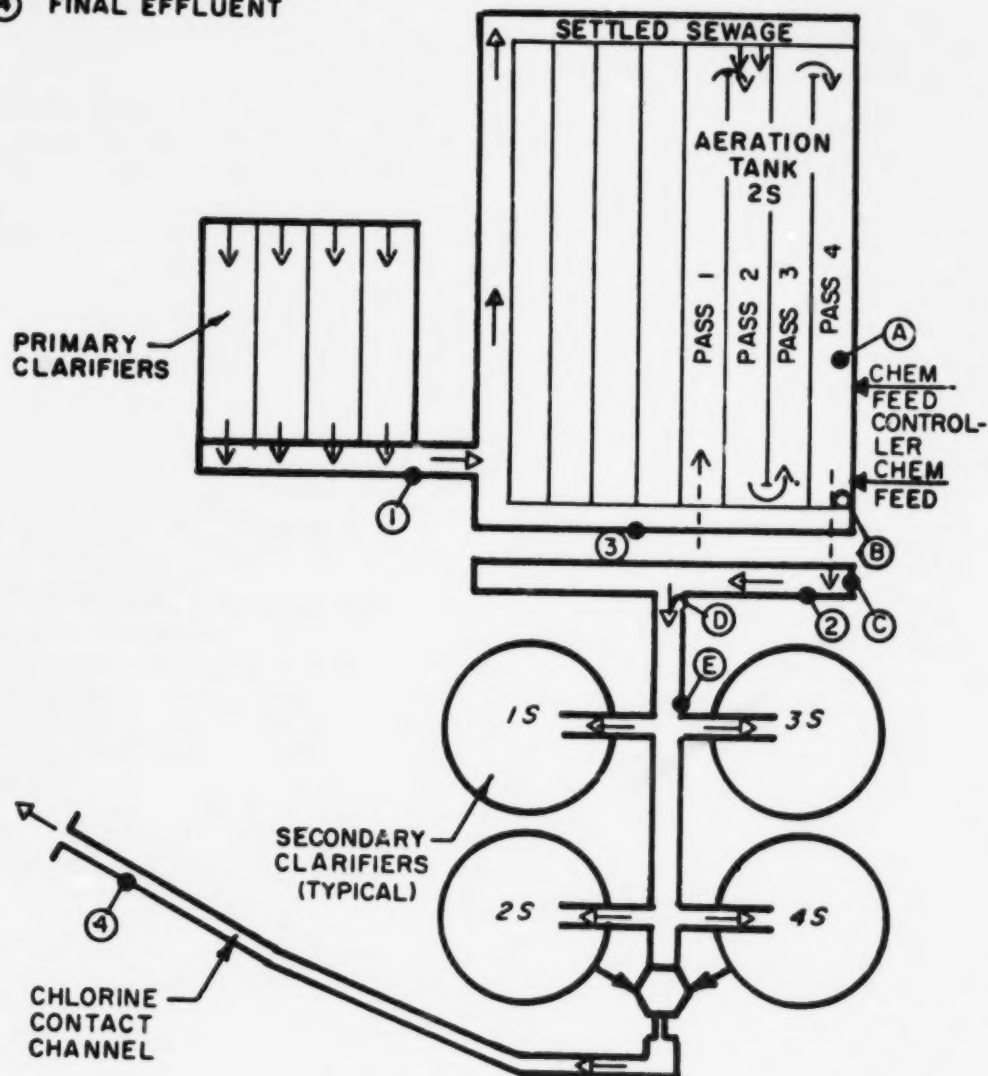


FIGURE 17
SAMPLING AND CHEMICAL ADDITION POINTS

Table 11. ANALYSES AND SAMPLE FREQUENCY-FULL SCALE
CHEMICAL FIELD TESTS

Chemical	Analyses	1 Primary Effluent P	2 Mixed Liquor M.L.	3 Return Act. Sludge RAS	4 Final Effluent F
Alum	SS	every 3rd hour	every 3rd hr	every 3rd hour	every 3rd hour
	VSS	" " "	" " "	" " "	" " "
	BOD ₅	" 4th "	--	--	" 4th "
	*Al	" 5th "	--	--	" 5th "
	**Total P	hourly	hourly	hourly	hourly
	Ortho PO ₄ -P	--	--	--	from 0800-2000 daily
	pH	--	hourly	--	--
	Settling	--	"	--	--

* For FeCl₃ feed Fe test was run at the same frequency.

** Samples were stored for later analysis.

nate following settling and decanting. The alkalinity and pH of the samples collected between 2100 and 0600 were measured by the operations personnel. Table 11 provides a list of analyses run as well as the frequency for each analysis at each sampling location. The frequencies in this table represent the final minimum number of analyses run with the initial schedule being more intensive.

Chemical addition was through a 40 inch long PVC tee which had 1/4" holes at 5 inch intervals along the top edge. This "diffuser" was situated directly above an aeration header approximately forty feet from the end of the aeration tank and four feet below the water surface. Mixing was provided by the aeration in the aeration tank while low energy flocculation was provided in the aerated mixed liquor distribution channel leading to the final clarifiers. Table 12 lists the average values of G (the rms Velocity Gradients) and the time of contact for both mixing and flocculation during both tests.

TABLE 12

Average Value of G - rms Velocity Gradient (Sec^{-1}) and Mixing Times

		Alum Feed	Iron Feed
Chemical	G	137.8 sec^{-1}	143.1 sec^{-1}
Mixing	Contact Time	8 min.	8 min.
Chemical	G	60.5 sec^{-1}	64.0 sec^{-1}
Flocculation	Contact Time	30 min.	30 min.

Alum, which was fed during the first full-scale test, was stored in a rented tank truck which was pressurized to 25 psi to provide pressure delivery to the aeration tank. The chemical feed rate was controlled by the chemical feed control system, as discussed earlier. A minimum testing period of fourteen days, which was at least two cell residence times, was selected in order to insure that equilibrium was reached. The alum feed test was conducted for a total of seventeen days from June 14th through July 1st.

As might be expected when placing a new system into operation, some initial problems were encountered. The majority of these problems were related to the chemical feed control system including:

1. Initial reagent imbalance in the phosphate analyzer resulting in inaccurate phosphorus residual signals.
2. Mechanical problems in the computer section of the controller which resulted in a considerable zero point drift.
3. A sticking chemical feed control valve.
4. Limitations in the feed system which required that the storage tank be depressurized and the alum feed stopped whenever the tank was being filled.

All of these problems were corrected or eliminated either during or at the completion of the alum feed test.

An aluminum to phosphorus ratio of 1.8 to 1 was initially selected on the basis of the jar scale test results. This ratio was increased to 2.0 to 1 beginning at 0800 on June 21st as a result of increasing effluent phosphorus levels. It was held at that level throughout the remainder of the test.

The raw data gathered during this test are available on a loan basis from Metro. The daily totals for pounds of primary phosphorus, mixed liquor supernate phosphorus, and final phosphorus, as well as average daily aluminum to phosphorus ratios, percent secondary phosphorus removals, plant flows and effluent phosphorus concentrations are presented in Table 13. The overall sums and averages of these values over the entire test period are also presented in this table. Daily and average solids data for the thirteen day period preceding the alum feed test as well as for the period of the test are presented in Table 14.

As the data in Table 13 show, a significant removal of phosphorus occurred between the primary effluent and the mixed liquor. This removal continued to evidence the same weekly removal cycle which was discussed previously. Over the period of the test, the aluminum to phosphorus weight ratio averaged 2:1. Secondary phosphorus removals averaged 73% with the effluent phosphorus residual averaging 2.1 mg/l. The data on this table is based on averages generated from the hourly samples. Mixed liquor phosphorus poundage was calculated using the sum of the effluent and return sludge flows while all other poundages were calculated using the effluent flow.

Table 13. DAILY AVERAGES AND TOTALS
FULL-SCALE ALUM FEED TEST

Date	Effluent Flow MG	lbs. Prim Total P	lbs. Soluble M.L. Ortho-P	lbs. Final Total P	lbs. Al	Average Al:P ratio (Wt.)	Average Secondary Total P Removal %	Average Final Total P mg/l
6-14	24	1418	843	649	3493	4.14	54.23	3.2
6-15	25	1732	847	242	1820	2.15	86.04	1.2
6-16	24	1507	553	251	1647	2.98	83.38	1.2
6-17	23	1193	375	189	648	1.73	84.14	1.2
6-18	25	1713	892	474	1758	1.97	72.33	2.3
6-19	24	1774	1037	472	1541	1.49	73.39	2.4
6-20	22	1621	1352	530	1623	1.20	67.31	2.9
6-21	25	1876	1106	588	2039	1.84	68.65	2.8
6-22	24	1600	987	352	2186	2.22	77.99	1.8
6-23	24	1636	687	299	1403	2.05	81.71	1.5
6-24	27	1585	871	486	1588	1.87	69.37	2.2
6-25	25	1593	810	403	1629	2.01	74.68	1.9
6-26	24	1437	831	461	1362	1.64	76.94	2.3
6-27	22	1570	387	343	1134	2.93	78.19	1.9
6-28	26	1891	1203	598	1931	1.61	68.37	2.8
6-29	25	1710	989	499	1641	1.66	70.80	2.4
6-30	25	1516	525	466	1207	2.30	69.29	2.2
Total	414	27,375	14,245	7,302	28,649	2.00	73.33	2.1

Table 14. ALUM FEED TESTS-SOLIDS DATA

DATE 1971	RAS mg/l	RAS VS %	RAS WASTE lb	SS WASTE OVER WEIR lb	TOTAL lb WASTE	SVI	SLUDGE DENS.	lb. SS UND. AGR.
June								
1	5490	79	6,399	3,621	10,019	88	1.14	93,740
2	6180	76	5,154	4,431	9,585	85	1.13	
3	5980	73	5,885	5,663	11,548	86	1.16	
4	6320	74	10,542	4,620	15,162	51	1.96	
5	7060	75	12,365	3,924	16,289	91	1.10	
6	6760	76	2,457	2,674	11,131	86	1.16	
7	6400	75	10,141	3,075	13,216	85	1.05	
8	6360	75	13,261	1,115	14,376	103	0.97	
9	6920	74	14,423	4,704	19,127	82	1.00	
10	6700	77	15,646	3,300	19,946	104	0.96	
11	8900	79	22,267	1,540	23,807	82	1.22	
12	6540	79	15,218	2,092	17,310	113	0.83	
13	5900	83	14,023	2,002	16,030	115	0.87	103,402
Total	68400		154,400	42,766	197,166		14.74	
Average	6569	76	11,804	3,290	15,173	92	1.13	4,663
14	5920	74	12,237	2,640	15,477	114	0.83	105,070
15	5340	69	12,025	3,534	15,609	85	1.13	
16	6960	69	17,024	3,225	21,219	83	1.20	
17	6,389	67	13,623	2,704	21,327	79	1.26	
18	5520	64	17,034	3,030	20,114	81	1.23	
19	5820	64	12,135	3,240	15,375	77	1.30	
20	5740	64	11,962	2,388	14,356	75	1.33	
21	6520	66	12,507	4,014	16,521	66	1.51	
22	5020	63	11,376	2,828	14,204	73	1.37	
23	7220	64	17,462	3,655	21,117	63	1.50	
24	7600	66	18,475	5,244	21,723	63	1.47	
25	7500	64	23,143	4,660	27,803	67	1.49	
26	7400	64	22,835	3,672	26,507	62	1.61	
27	6100	63	16,220	4,305	20,525	63	1.50	
28	6160	64	15,412	2,964	18,376	61	1.64	
29	6380	61	11,706	3,220	14,926	61	1.64	
30	6620	65	14,354	3,330	17,684	56	1.73	
July 1	6320	62	16,267	2,231	18,093	66	1.51	112,240
Total	116320		291,037	60,984	342,021		25.53	
Average	6462	65	15,613	3,393	19,001	72	1.42	7,173

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Examination of the solids data leads to several interesting conclusions. As would be expected, there was a definite increase in the production of solids as compared to a normal period when alum was not being added. This increase was equal to 3830 lbs. per day or approximately 25% greater than for the reference period. The volatile content of the sludge decreased at the same time from an average of 76% to 65%. It had stabilized in the range of 62%-64% by the end of the test. This is in agreement with the fact that inorganic solids were being added to the system.

The sludge volume index was also affected significantly by the alum addition. The average SVI for the reference period was 92 while the average during the addition period was 72. The final SVI leveled off in the range of 60-65. This decrease in the SVI is of significance, especially when combined with the increase in solids production, since it represents an increase in the settleability and thus the density of the sludge after a 30 minute settling period. Thus, even though there was a 25% increase in the pounds of sludge produced, there was at least a 30% increase in the sludge density compared to the reference period. Such an increase would result in a decrease in the sludge volume despite the increase in the pounds of sludge produced.

Other investigators have reported that alum addition resulted in excessive turbidity and solids loss in the effluent (93, 94). However, there was no appreciable increase in the effluent suspended solids while there was an improvement in the turbidity and transparency during the alum feed test. This improvement was greatest during the first few days of the test when turbidities of less than 1.0 JTU and transparencies of greater than 70 inches were recorded. A malfunction in the feed controller which resulted in a very aluminum to phosphorus ratio during the first day of the test might have been partially responsible for this very rapid improvement. This condition was corrected and there was a slow decrease in the transparency and increase in the turbidity through the first week of the test, after which they stabilized at values which were still better than normal.

Despite the better than normal transparencies and turbidities, there was no significant decrease in the pounds of solids escaping with the effluent. This was attributed to the large decrease in the SVI which, though indicating a significant degree of flocculation and improvement in the settleability of the majority of the floc, allowed straggler floc, which was not captured by the rapidly settling sludge, to escape in the effluent. As was stated previously, the

degree of this problem was not sufficient to create an increase in the pounds of solids in the effluent.

The solids removal during both periods averaged better than 94% and there were no indications of biological upset resulting from the alum addition at any time during the test. Although the volatile content of the activated sludge decreased, it equilibrated at an acceptable level. BOD_5

removals remained excellent with the effluent BOD_5 averaging in the 3-6 mg/l range on the basis of 5 daily flow paced composite samples which are recorded in the plant monthly report. Microscopic examination of the sludge also indicated that no problems were occurring as can be seen in Figures 18, 19, and 20 which are pictures which were taken prior to, at the middle, and at the end of the alum feed test, respectively. The sludge was well flocculated and the protozoa remained numerous and active throughout the test.

During the period of the alum feed test a total of 414 million gallons of sewage were treated while a total of 50,700 gallons of alum (8.3% Al_2O_3) which corresponds to 138 tons of 17% Al_2O_3 were fed. The cost of alum during this period was \$50.55 per ton of 17% Al_2O_3 f.o.b. factory.

The total chemical cost for the test was \$6,920.00 or \$16.80 per million gallons treated, while the effluent phosphorus concentration averaged 2.1 mg/l and the secondary phosphorus removal averaged 73.3%. On the basis of the quantity of alum used and the quantity of phosphorus removed, the treatment cost was \$2.88 per mg/l phosphorus removed per million gallons, which corresponds to an average secondary phosphorus removal of 5.8 mg/l. The total cost per million gallons can be expected to increase as the level of primary phosphorus increases, and as the desired effluent phosphorus concentration decreases. The magnitude of this cost increase in terms of dollars per mg/l of P removed per million gallons will be a function of the initial phosphorus concentration and the desired final phosphorus residual.

In general, the reaction of aluminum in water containing phosphorus can be viewed as a combination of two competitive reactions. These two reactions are hydrolysis in which the aluminum reacts with the water to form insoluble aluminum hydroxide and free hydrogen ions and phosphorus precipitation in which the aluminum reacts with the phosphate to form insoluble aluminum phosphate. Both of these reactions occur very rapidly with the rate for the



Figure 18
Biological Floc Before Alum Feed



Figure 19
Biological Floc During Alum Feed



Figure 20
Biological Floc at the End of the Alum Feed

hydrolysis reaction being a function of the pH and the aluminum ion concentration while the phosphate precipitation reaction rate is a function of the aluminum ion concentration and the phosphate ion concentration.. Since a change in the phosphorus concentration would not be expected to affect the pH, the hydrolysis rate would be expected to be constant while the rate of phosphorus precipitation would vary in direct proportion to the phosphorus concentration. For this reason, the cost to remove one mg/l of phosphorus from a given volume would be less at high phosphorus residuals than at low phosphorus residuals. In addition this cost would increase prohibitively as the desired final phosphorus residual is decreased due to the almost total loss of aluminum as the hydroxide.

The second full-scale test, during which ferric chloride was fed, was conducted between August 9th and August 23rd, 1971. Prior to beginning this test, the mechanical and chemical problems which had been encountered in the chemical feed control system during the alum feed tests were corrected.

The ferric chloride was stored in two 15,000 gallon vinyl, above-ground swimming pools. The solution was protected from contamination by a polyethylene sheet which was floated on the liquid surface.

A centrifugal chemical pump was used to deliver the iron solution to the aeration system. Since the capacity of the pump was significantly greater than the required ferric chloride flow rate, a bypass line, which went from the discharge side of the pump to the storage tank, was installed to prevent excessive pressure buildup when flow to the aeration tank was limited by the diaphragm control valve. This allowed the majority of the liquid pumped to be returned to the storage tank while just enough chemical to satisfy the controller demand was fed to the aeration system. This system had the additional advantage of insuring homogeneity of the ferric chloride solution due to the mixing caused by the returned solution.

The corrections and modifications made in the chemical feed control system were successful and the control problems encountered during the alum feed test were eliminated. As a result, a much closer control over the feed rate was maintained during the iron feed test. The major problems encountered during this test were related to the extremely corrosive nature of ferric chloride coupled with a lack of knowledge regarding compatible equipment on the part of both the suppliers and the investigators. The problems

which developed included:

1. The failure of all nylon fittings in the supply system which required a postponement of the iron feed test while they were replaced with PVC. Those fittings had functioned perfectly throughout the entire alum feed test, but began to fail within three hours after exposure to the ferric chloride.
2. Decomposition of the feed pump seals which required that a new pump be installed before the test could be continued. This pump was listed as compatible with ferric chloride by the supplier.
3. Corrosion of the rotometer seals toward the end of the test period. The rotometer had been used during the alum feed test with no apparent decomposition. It had been purchased with the understanding that it was compatible with both alum and ferric chloride.

In addition to its corrosiveness, the ferric chloride stained concrete and galvanized railing around the storage tanks, killed the lawn where it was spilled and stained the clothing and skin of the personnel working around the area. While these characteristics are unrelated to the ability of ferric chloride to remove phosphorus, they make it a difficult material to work with or around.

At the beginning of the test, an iron to phosphorus ratio of 3.6 to 1 was utilized on the basis of the jar scale test results. The ratio was increased to 4.0 to 1 at 1700 on the 12th because the effluent phosphorus level was still above 2 ppm. This ratio was maintained to the end of the test.

The raw data collected during the iron test is available from Metro on request. Daily averages of the iron to phosphorus ratio, plant flow, percent secondary phosphorus removal, final effluent phosphorus concentration, total pounds of primary phosphorus, mixed liquor supernate phosphorus, final phosphorus and pounds of iron fed are presented in Table 15. This table also includes the overall sums and averages of the above data for the test period. Average and daily solids data for the test period and a thirteen day reference period just preceding the test are presented in Table 16.

As an examination of Table 15 shows, there was again a significant phosphorus removal between the primary effluent and the mixed liquor. The iron to phosphorus weight ratio averaged 4.80 which significantly exceeded the ratio set on the feed control system. This discrepancy was the

Table 15. DAILY AVERAGES AND TOTALS
FULL-SCALE IRON FEED TEST

Date	Effluent Flow MG	lbs. Prim. Total P	lbs. Soluble H.L. Ortho-P	lbs. Final Total P	lbs. Iron	Average Fe:P Ratio (Wt.)	Average Secondary Total P Removal %	Average Final Total P mg/l
8-10	19	1351	1119	451	5297	4.74	66.63	2.8
8-11	22	1481	956	329	4102	4.29	77.77	1.8
8-12	22	1384	927	379	4516	4.87	72.62	2.1
8-13	22	1298	622	245	1620	2.61	81.13	1.3
8-14	20	1353	625	240	3355	5.37	82.29	1.4
8-15	20	1342	889	228	4573	5.14	82.98	1.4
8-16	22	1583	1114	253	5262	4.72	84.04	1.4
8-17	22	1344	753	198	3780	5.02	85.29	1.1
8-18	22	1551	937	247	4343	4.64	84.09	1.3
8-19	21	1136	500	258	3160	6.31	77.32	1.5
8-20	22	1318	804	189	4171	5.19	85.69	1.0
8-21	21	1492	1054	234	4768	4.53	84.32	1.3
8-22	20	1140	531	127	3010	5.67	88.87	0.8
Totals	275	17,773	10,832	3376	51,958	4.80	81.01	1.5

Table 16. IRON FEED TEST-SOLIDS DATA

DATE 1971	RAS mg/l	RAS VS %	RAS WASTE lb	SS WASTE OVER WEIR lb	TOTAL lb WASTE	SVI	SLUDGE DENS. %	lb. SS UND. AER.
July								
27	5160	74	11,130	3,465	14,654	94	1.06	92,235
28	5600	77	11,670	2,361	14,037	91	1.10	
29	4530	78	12,037	3,094	16,081	93	1.07	
30	5340	76	15,537	2,132	17,769	102	0.98	
31	5000	73	15,420	2,912	18,341	95	1.05	
Aug.								
1	4340	75	9,049	2,587	11,636	70	1.43	95,906
2	4840	75	0	3,433	3,488	80	1.25	
3	5480	75	10,512	2,167	12,679	81	1.23	
4	5560	79	12,003	7,245	20,229	79	1.26	
5	4760	80	13,497	1,935	15,432	76	1.31	
6	4630	79	11,319	3,435	14,804	79	1.26	
7	5000	77	8,340	3,696	12,036	85	1.18	
8	5630	76	9,860	3,859	13,719	77	1.30	
Total	65970		142,420	42,476	184,905	1102	15.48	
Average	5075	76	10,956	3,267	14,223	85	1.19	3,621
Aug.								
9	4070	76	9,119	3,535	12,704	63	1.59	98,492
10	5140	75	11,574	2,288	13,862	78	1.28	
11	5760	75	16,138	1,260	17,388	84	1.19	
12	6020	73	17,572	2,893	20,470	88	1.14	
13	5960	67	19,832	2,100	21,932	87	1.15	
14	5340	72	19,432	1,949	21,431	86	1.16	
15	5060	64	15,614	1,140	16,754	94	1.06	
16	5460	66	13,661	1,050	14,711	86	1.16	
17	6010	64	14,536	1,260	15,796	84	1.19	
18	6420	63	14,992	2,460	17,452	86	1.16	
19	6360	69	16,443	2,084	18,527	99	1.02	
20	6220	55	16,543	1,484	18,027	115	0.87	
21	6300	63	19,966	792	20,758	115	0.97	
22	6280	58	19,902	2,364	22,266	98	1.14	111,597
Total	81900		225,414	26,714	252,128		15.98	13,105
Average	5350	67	16,101	1,908	18,009	89	1.14	

result of an incorrect alignment of this system. Since the ratio was being set empirically based on the phosphorus removal. Secondary phosphorus removals averaged 81% with the effluent phosphorus concentration averaging 1.5 mg/l. These data were calculated as was discussed previously for the alum data.

The iron addition, as was the case with the alum addition, resulted in an increase in the daily production of solids and a corresponding decrease in the volatile solids content of the sludge as compared to the reference period as is shown in Table 16. The increased solids production was 4,440 pounds per day or approximately 25%. The volatile solids content dropped as low as 55% after less than 13 days of iron feed and it appeared to be dropping further at the time the test was discontinued. Such a drop in the volatile content of the sludge could indicate a conversion from a biological to a chemical floc system which would destroy the effectiveness of the biological system.

The sludge volume index was unchanged during the iron feed test and the averages before and during the test were in the range of 85-90. Since there was no change in the SVI and thus none in the settled sludge density, the sludge volume would be expected to increase by a factor of 25-30% in response to the increased sludge production. Such an increase in the sludge volume could be significant in a plant which was already overloaded with solids.

The turbidity and clarity of the effluent improved during the iron feed test as compared with normal conditions. Turbidities stayed in the range of 1.5-2.0 JTU while the effluent BOD₅ averaged in the range of 2-5 mg/l. This improvement was accompanied by a decrease in the effluent solids concentration. The decrease in the effluent solids was attributed to the excellent flocculent characteristics of ferric chloride which were not counteracted by a corresponding decrease in the SVI. Thus the iron caused the sludge to flocculate and helped to trap and remove the straggler floc which would have escaped to the effluent if the SVI had been decreased as well. Solids removal during this period averaged better than 95%. Microscopic examination of the floc showed no decrease in the biological activity of the protozoal population. The floc was well formed, but it began to take on a rusty color as the test proceeded. The condition of the sludge prior to, in the middle and at the end of the iron feed is shown in Figures 21, 22, and 23, respectively. The darkening of the floc evident in the last slide could correspond to the increased inorganic content which was referred to earlier.

A total of 275 million gallons of sewage were treated during the iron feed test while a total of 25,600 gallons of 43% ferric chloride which is the equivalent of 70.8 tons of anhydrous ferric chloride were fed. The cost of the ferric chloride as delivered was \$209 per ton, however, delivery accounted for a significant part of the cost. The f.o.b. the factory cost was quoted as \$143 per ton of anhydrous ferric chloride. Based on the cost at the factory, the chemical cost for the iron addition would have been \$34.20 per million gallons. The effluent phosphorus concentration averaged 1.5 mg/l and the secondary phosphorus removal averaged 81.0%. When the chemical cost is converted to terms of dollars per mg/l of phosphorus removed per million gallons, the result is \$4.40. This corresponds to an average removal of 6.2 mg/l of phosphorus in the secondary. As was discussed previously, this figure would increase as the final phosphorus level was decreased as a result of kinetic considerations.

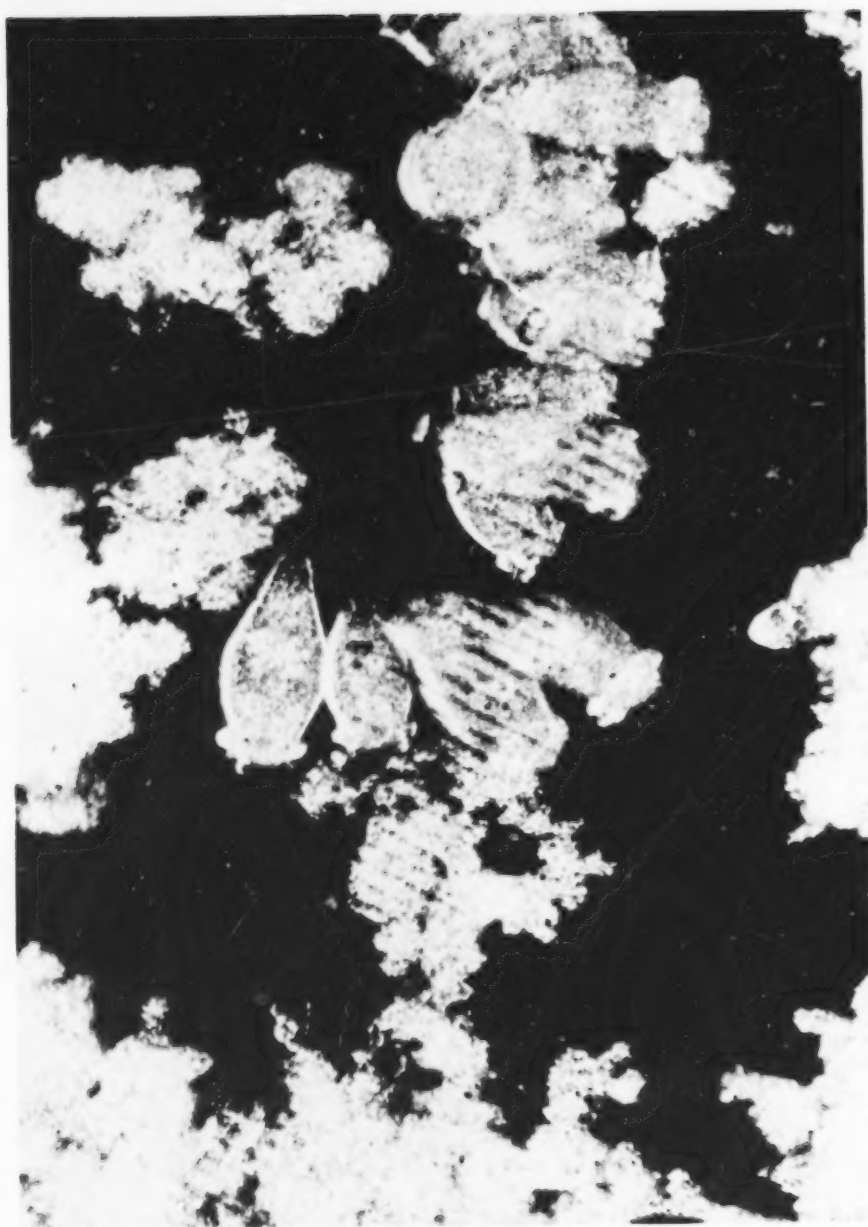


Figure 21
Biological Floc Before Ferric Chloride Feed



Figure 22
Biological Floc During Ferric Chloride Feed

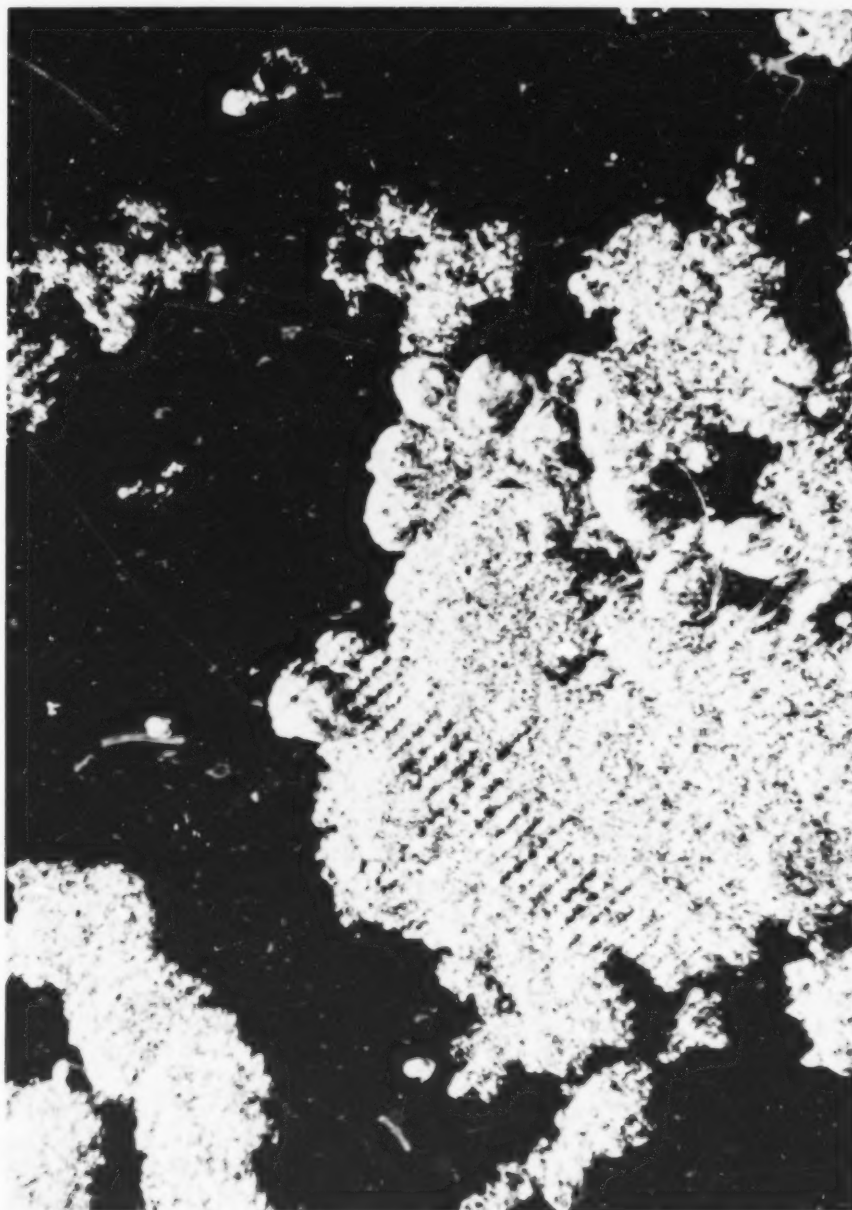


Figure 23
Biological Floc at the End of the Ferric Chloride Feed

SECTION IX

DISCUSSION

This study involved the use of methods of research ranging from straight literature review to full scale testing of both biological and chemical methods of phosphorus removal. The results obtained using each of these methods are discussed herein.

Biological Tests

Both bench scale and jar scale tests were in general agreement. The uptake of phosphorus was not affected by dissolved oxygen levels within normal operating ranges (0.5-4.0 mg/l) nor was there a correlation between organic loading and phosphorus uptake. Both methods did indicate that there is a direct correlation between the concentration of the mixed liquor suspended solids and the removal of phosphorus. The jar scale test also showed some correlation between the phosphorus uptake and the product of the solids concentration and the hardness.

The results of full scale analyses showed that the removal of phosphorus was directly related to the organic loading and the magnesium uptake. That is, as the organic loading increased, the removal of both magnesium and phosphorus increased. These results are in agreement with previously published reports of a correlation between biological phosphorus uptake and magnesium uptake. This strongly suggests that the normal mechanism of phosphorus removal at the Renton plant is exclusively biological in nature. This conclusion is supported by the extremely low concentrations of magnesium and calcium in the influent stream which are below the equilibrium concentrations required for chemical precipitation.

Despite the tremendous volume and variety of data collected and analyzed, only 25% of the observed variability in phosphorus uptake could be statistically attributed to these variables. This means that other more subtle factors were responsible for the majority of the variation in the phosphorus removal. Further research needs to be done to determine the nature of those factors in order to provide the key to complete control of biological phosphorus removal.

Since the normal phosphorus removal mechanism at the Renton plant was of a biological nature, it would be expected that operation under conditions which would promote rapid

biological growth would provide maximum phosphorus uptake. This was confirmed during one phase of the full-scale study when operation under conditions of high waste rate and high aeration rate was found to provide maximum phosphorus removal. The magnitude of this removal will be directly dependent on the ratio of BOD to phosphorus entering the plant under a consistent mode of operation.

A comparison of the results obtained from the full-scale tests and those from the jar and bench scale tests showed that there was a significant difference between the two types of tests. The jar and bench scale tests were subject to numerous variables, including conditions related to the scale difference, which would affect the results and their relation to full-scale conditions. The advantages obtained from having a small system with completely controllable input parameters were outweighed by the disadvantages resulting from the significant difference between the model and the real systems. Jar and pilot scale studies were inadequate for developing realistic data on the biological operation of the full-scale facility.

Chemical Tests

The jar and bench scale chemical tests were in general agreement and showed that alum, ferric chloride and ferrous sulfate could be used equally well to remove phosphorus from a biological culture. They also showed that alum was significantly more effective than sodium aluminate under the conditions encountered at the Renton plant.

Under the normal conditions of pH encountered upon the addition of alum or ferric chloride to the activated sludge (i.e. pH 6.0 - 6.5) an aluminum to phosphorus weight ratio of approximately 3.6:1 was required to reduce the final phosphorus was found to occur instantaneously for both salts. The iron to phosphorus ratio was found to be the same for ferric chloride and ferrous sulfate, but there was a significant reaction time required for ferrous sulfate before complete precipitation occurred.

The aluminum to phosphorus ratio required for sodium aluminate was found to be approximately twice that for alum. This was attributed to the increase in pH to 8-9 which occurred when sodium aluminate was added to the activated sludge. The pH of the system gradually decreased with time to the range of 7 with an accompanying increase in the phosphorus removal, but the removal never reached the magnitude associated with the addition of a comparable amount of alum. Immediate adjustment of the pH to the 6.0-6.5 range resulted in an aluminum to phosphorus ratio equal to the 1.8:1 value

obtained with alum.

The importance of pH with respect to the ratio of aluminum to phosphorus removal was further investigated in a series of tests, the results of which can be obtained from Metro. The data from these tests showed that the required aluminum to phosphorus ratio increased from 1.6 to greater than 2.0 as the pH increased from 6 to 8. Such an increase can be explained by considering the acid dissociation of the phosphoric acid species and the deprotonation equilibrium of the hydrated aluminum species. Through these reactions, the phosphate species becomes more negatively charged (i.e. $\text{H}_2\text{PO}_4^- \rightarrow \text{HPO}_4^{2-} + \text{H}^+$) as the pH increases while the positive charge on the hydrated aluminum species becomes less (i.e. $\text{Al}(\text{H}_2\text{O})_5\text{OH}^{2+} \rightarrow \text{Al}(\text{H}_2\text{O})_4(\text{OH})_2^+ + \text{H}^+$) as the pH increases. The increase in the aluminum to phosphorus ratio thus becomes dependent on the ratio of charges on the two species and on the loss of aluminum as an insoluble hydroxide with increasing pH. A similar situation exists with iron, but the pH range is lower due to the different equilibrium constants.

One factor which jar and bench scale tests were unable to handle was the question of the effect of extended addition of iron or aluminum to the biological system. This was important because of the possible deleterious effects of such additions on the biological system and because of the need to determine whether there was a recycle effect on the phosphorus removal which would result in a decrease in the metal requirement for phosphorus removal with time. A series of continuous pilot scale studies were conducted to provide information on these subjects.

The addition of either iron as ferric chloride or aluminum as alum had no detrimental effects on the biological system although there was some change in the ratio of organisms present. The alum addition caused a decrease in the sludge volume index of the system while there was no change in the SVI during the iron addition. There was no recycle or turbidity effect observed with either chemical.

Unlike the biological jar and bench tests, the chemical jar, bench and pilot scale tests were excellent methods for developing operational data on the operation of chemical phosphorus removal systems. The full scale tests were necessary to obtain cost and chemical feed data for the full-scale system, but the initial small scale tests allowed for the selection of the most effective chemicals and addition points at a minimum of cost and with a minimum of time.

Both ferric chloride and alum functioned effectively during the full-scale tests. The selection of the best and most economical chemical on the basis of these tests is complicated by a number of factors. Alum was a far more attractive chemical than ferric chloride from the standpoint of ease of handling and lack of corrosiveness. Both chemicals could be controlled equally well using the type of control system discussed in the experimental section. A summary of the relevant data for each test is presented in Table 17.

As would be expected, the addition of either chemical resulted in an increase in the pounds of solids produced due to the additional chemical precipitate. Although the increase in sludge production during the iron test was greater than during the alum test, the difference was not as great as would be expected on the basis of the relative molecular weights of the two elements and the actual quantities of chemical added. This inconsistency was related at least in part to errors in the measurement of the waste RAS flow. The accuracy of this measurement was such that a significant error might result. Another likely source of error was the method used to calculate the increased sludge production, which depended on a comparison of sludge produced during the period of chemical feed to sludge produced during an arbitrary period preceding each test. The parenthesized figures in Table 17, which are data for the control periods, show that there were changes in loading and detention times between the control and test periods which could easily result in errors in the calculated increase in sludge production caused by the chemical additions. Under any circumstances, the use of iron would be expected to produce approximately one third more chemical sludge at the weight ratios used in these tests.

The increased solids production was counteracted in the case of alum by an accompanying increase in the sludge density while no such density increase was observed with the iron addition. Both tests were operated with beginning SVI's of approximately 85 which might partially explain the lack of change in the iron test. Some increase in the sludge density might have been obtained during the iron test if the starting SVI had been higher. Since alum reduced the SVI below 85 while iron was unable to do so, this increase would be expected to be less than for the alum. Thus, the use of alum would be expected to result in a significantly smaller volume of solids than would the use of ferric chloride.

The average phosphorus residual in the effluent was somewhat less and the percent secondary phosphorus removal was greater during the iron test than during the alum test. This

Table 17.

SUMMARY OF FULL-SCALE CHEMICAL FEED TEST RESULTS		
Parameter	Ferric Chloride	Alum (Aluminum Sulfate)
Duration of test (days)	14	17
Volume Treated (million gallons)	275	414
Volume of Chemical Used (gallons)	25,571 (43% FeCl_3)	50,700 (8.3% Al_2O_3)
Weight of " " (tons)	70.8	138 (17% Al_2O_3)
Cost of Chemical Excl. shipping	\$10,124	\$6,920
Average Chemical to Phosphorus Weight Ratio	4.80:1	2.0:1
Sludge Volume Index-before addition	84	88
Sludge Volume Index-after addition	88	62
Final Effluent Total Phosphorus (ppm)	1.5	2.1
Average Secondary Removal (%)	81	73
Total Pounds Phosphorus Removed	14,396	20,073
Total Pounds Phosphorus Discharged	3,376	7,302
Treatment Cost (\$/mg/l removed/MG)	\$5.86	\$2.88
Cell Residence Time (days)	5.8 (6.7)	5.7 (6.7)
Average Aeration Time (hours)	5.58 (5.30)	5.30 (5.20)
Average BOD Loading (lbs BOD/100 lbs. MLVSS)	24.6 (25.6)	27.4 (29.3)
Increased Sludge Production (lbs./day)	4443	3829

difference can be explained as resulting from controller problems during the alum test and the fact that the ratio of iron to phosphorus was greater than the ratio of aluminum to phosphorus on a stoichiometric basis. Such a difference could be corrected by increasing the aluminum to phosphorus ratio. This would, of course, result in an increase in the cost of the treatment.

Although the full-scale tests generally agreed quite well

with the jar and bench scale tests, the removals obtained at the same metal to phosphorus ratio during the jar and bench tests were significantly better than for the full-scale tests. One of the major causes for this was a lack of adequate mixing during the full-scale tests as demonstrated by the G values at the mixing point. These values, which were in the range of 150^{-1} were significantly less than the value of 1000 sec^{-1} which has been recommended (EPA Technology Transfer Seminar-Seattle, Washington, 1972). As a result, it seems likely that significant quantities of metal were lost through hydrolysis and precipitation in forms other than insoluble phosphate. If this were the case, a more effective method of mixing would be required to provide the maximum efficiency for phosphorus removal. The method used would have to be adapted to the hydraulic configuration of the system to which chemicals are being added.

The chemical feed and control system utilized during the full-scale tests performed well considering the experimental nature of the system, but certain improvements would be required to maximize the efficiency of the system. To provide protection for the analytical equipment as well as the personnel servicing the system, the system should be installed in a permanent structure. The portable cabinet served adequately during the test period, but would not be satisfactory for continuous use. The flow signal used during the test period was the effluent sewage flow rather than the sum of the effluent and return sludge flows because of the difficulty associated with producing such a figure for a short term test. Since the return rate was controlled as a percentage of the effluent flow, it was possible to manually compensate for this lack during the testing period while adjusting the ratio set point. While this adjustment was adequate for the testing period, a combined flow signal should be provided for a permanent installation.

Another flow measurement critical to the proper control of the chemical feed is the chemical flow rate. A transmitting rotometer was used during the full-scale tests, however, corrosion and sticking of the rotometer were fairly serious problems. An alternative to a rotometer such as a magnetic flow meter or a metering pump would be preferable.

The automatic analyzer used in the control system worked very well. Such a system should be provided with a direct signal from the colorimeter to the computer rather than utilizing a logarithmic cam as was done in the experimental system. The colorimeter signal should be converted to a logarithmic function prior to use as a control signal if this is not automatically done by the colorimeter. The concen-

tration signal should be connected to both high and low level alarms since these are necessary to give warning of an analyzer malfunction as well as to protect against either over or under feeding of the chemical. Although it is not critical to the control of the chemical addition, it is advisable to install a phosphorus analyzer in the final effluent. Such an installation would provide back-up coverage and, if equipped with a high level alarm, would call attention to any malfunction in the system.

The addition of both alum and ferric chloride caused a reduction in the mixed liquor pH from its normal level of 7.0-7.2 to 6.5 at the point where it entered the final clarifiers. The pH reduction was even greater immediately after the chemical addition, but the biological activity resulted in an increase to the 6.5 value during passage through the mixed liquor distribution channel to the clarifiers. The pH depression did not affect the biological activity with respect to BOD₅ and suspended solids removal, but it may have been responsible for an inhibition of nitrification which was observed during both full-scale tests. However, the cell residence times during both tests were lower and the organic loadings were higher than during the control periods, which would also result in a decreased level of nitrification during the test so it could not be determined whether it could be achieved if it were desired.

While the pH reductions experienced during full-scale tests were not excessive, this could be a problem in systems having high phosphorus levels and/or low alkalinities. Systems having alkalinities significantly less than 150 mg/l or influent phosphorus levels greater than 10 mg/l might find it necessary to control pH while adding chemicals. One possibility would be the use of sodium aluminate in combination with alum or ferric chloride to maintain the pH at an acceptable level.

The addition of the two chemicals caused a decrease in the volatile content of the activated sludge as a result of the accumulation of chemical sludge. This decrease had stabilized at an acceptable level during the alum feed test, but the volatile content was still decreasing at the end of the iron feed test. This loss of volatile content of the activated sludge during the iron feed could have corresponded to a conversion from a biological to a chemical system and, as such, would be a serious problem for continuous chemical addition. The magnitude of this problem was increased by the low BOD₅ loading at the Renton plant. It seems likely that no such problem would exist at a facility where the loading and thus the biological growth rate is higher.

The design of a chemical feed system to be added to an existing activated sludge plant would be similar whether alum or ferric chloride are used. A larger storage capacity would be required for alum than for ferric chloride, but the best procedure is to design the system so that either chemical can be used depending on the results of experimentation. The piping for the system should be entirely PVC and should allow for a wide flexibility in the selection of dosing points. The chemical pump should be a heavy duty model designed to handle corrosive materials such as ferric chloride.

Fiberglass storage tanks provide the best answer to chemical storage in terms of cost and maintenance. They can be used to store either chemical and are much more reliable than rubber lined steel tanks. If a minimum of seven days storage is desired, a minimum storage volume of approximately 1000 gallons per million gallons of daily flow will be needed assuming an influent phosphorus level in the 8 to 10 mg/l range, and an aluminum to phosphorus ratio of 2.0:1. A smaller storage volume will be required if ferric chloride is selected, but sizing the tanks for alum provides greater flexibility. The approximate cost of the chemical feed control system is in the range of \$10,000 to \$12,000 including everything except the storage tanks. The automatic analyzer system accounts for approximately \$7,000 of this figure. The number of chemical feed points in the plant will determine the number of chemical feed control systems required. Thus, if the feed point is the end of the aeration tank, one system per aeration tank will be required. However, if the aeration tanks discharge to a central distribution channel, provisions could be made to supply rapid mix in this channel and thus minimize the number of control systems required. It is important to insure that adequate detention time remains after the chemical addition to insure proper flocculation.

An analyzer for the final effluent would cost an additional \$7,000 but it would provide additional security with respect to system malfunctions. The costs for the autoanalyzer systems are based on the system used during the full-scale test. Less expensive systems may be available, but they must have a prefilter capable of removing the quantity of biological solids normally encountered in activated sludge mixed liquor.

The major cost associated with chemical feed for phosphorus control is the cost of chemicals. These costs in turn will be strongly dependent upon the location of the chemical producer with respect to the treatment plant. Since trans-

portation costs are variable depending on location, no attempt was made to provide data on shipping costs of the chemicals. The costs of the chemicals are based on the cost F.O.B. the factory in the case of both the alum and the ferric chloride.

On the basis of the full-scale tests, alum was fed at an average rate of 120 gallons (8.3% Al_2O_3) per million gallons while ferric chloride was fed at a rate of 98 gallons per million gallons. This corresponds to a cost of \$16.80 per million gallons for alum versus a cost of \$34.20 per million gallons for ferric chloride under the conditions found at the Renton treatment plant. The chemical costs based on removal of phosphorus were \$2.88 per mg/l of phosphorus removed per million gallons for alum and \$5.86 per mg/l of phosphorus removed per million gallons for ferric chloride.

Either alum or ferric chloride can be effectively used to remove phosphorus by addition to the activated sludge. Even though the final phosphorus residual obtained during the alum test was greater than the final phosphorus concentration during the ferric chloride test, alum is the chemical of choice for use at the Renton plant. This choice is based on the greater ease of handling, the enhancement of the sludge settleability and the greater economy associated with the alum. The additional cost required to bring the residual to the same level as achieved with the ferric chloride would not be great enough to make the ferric chloride less expensive and the cost factor is of necessity the major factor. Implementation of the recommendation for more efficient mixing would very likely reduce the cost of both chemicals significantly, but it would not change the relative costs of the two.

The cost advantage of alum over ferric chloride is greatly increased at the Renton plant since alum is produced within 20 miles of the plant while the nearest producer of ferric chloride is over 1000 miles away in central California. It will be necessary for each plant considering the use of these chemicals for phosphorus removal to price the chemicals based on their local situation. It is possible that the transportation costs will change the economic order of the two chemicals at which time the greater ease of handling and the better sludge settleability obtained with alum become significant factors.

SECTION X

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